THE REIGNITION OF AN ARC AT LOW PRESSURES

Thesis by

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SUMMARY

This thesis presents the results of a study of the factors influencing the reignition potential of an alternating current arc. The data were obtained from voltage oscillograms of arcs between electrodes of different materials, in several gases at pressures from 2 cm. of Hg. to atmospheric, for a gap of 1 mm. and a series of currents.

It was found that at low pressures the reignition potentials of copper, graphite and carbon were approximately the same, essentially independent of current, proportional to the pressure and lower than the sparking potential. At moderate and high pressures the reignition potential decreased with increases in the current, this effect being pronounced for graphite and carbon which acted exactly as a metal under these conditions for low currents. It was found that when the current in a graphite or carbon arc was increased beyond a certain value the reignition potential decreased with the increases in pressure. This effect was not present in the case of the metals.

Impurities having a low work function are shown to decrease the reignition potential markedly. Conditions favoring a high temperature of the electrodes also tend to decrease the reignition potential. The results are shown to be consistent with a theory of the transition from a glow to an arc proposed by Dr. S.S. Mackeown, under whose direction this research was done.

A paper covering part of the experimental results has been accepted for publication in Electrical Engineering.

INTRODUCTION*

It has been shown in recent papers on the subject that the material of the electrodes of an alternating current arc influences the arc reignition to a marked degree. Thus, Todd and Browne[11] have shown that the potential required to restrike an alternating current arc when the current reverses is low and of the order of the burning potential at atmospheric pressure, providing the electrodes are of carbon or tungsten. However if the electrodes are of copper, brass, or other material that cannot exist in the solid state at very high temperatures, the potential necessary to restrike the arc is very high compared to the burning potential. It is well known that in order to supply sufficient thermions to yield the large current densities found in the region of the cathode spot a temperature exceeding 3000°K is necessary. Both carbon and tungsten are solid at this temperature and it is extremely probable that with these materials both electrodes of an alternating current

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*See Bibliography for all references.

arc are at a sufficiently high temperature to furnish all the electrons necessary for carrying the arc current by thermionic emission.

With electrodes of material that is not solid at these high temperatures it is necessary to postulate some other mechanism of producing the large electron current that exists in the region of the cathode spot. A highly acceptable theory of the cathode drop in the cases where the electrodes cannot exist at very high temperatures, is that the electrons are drawn out from the cathode by the action of the extremely high electric fields that exist there. These electric fields have been shown by Dr. Mackeown[2] and quite recently by Wyer[48] to be of the order of 10^6 volts per centimeter and are due to the formation of a positive ion sheath at the cathode. This sheath constitutes the cathode drop and occurs in a region very close to the cathode, less than 3×10^{-5} centimeters from the surface. When the current in an alternating current arc reverses, it is necessary to produce this very high electric field at the surface of the electrode which was formerly the anode. In order to do this it is assumed that a glow discharge first forms with its relatively high cathode drop, extending over a relatively large distance. As the current in this discharge increases, the current density reaches a limit at which the discharge changes to an abnormal glow and the magnitude of the cathode drop increases and at the same time the region over which this drop exists decreases; both of these effects producing an increase in the strength of the electric field existing at the cathode. At some critical value the large cathode drop of the glow discharge collapses into the low cathode drop of the arc which, however, extends over a very small region. Transition from a glow to an arc occurs very rapidly if the current is high, but it must occur at every reversal of the current, and a relatively high restriking potential is necessary if the electrode material is not a solid at a very high temperature.

Another theory of the cathode drop is that sufficient ionization takes place by the spontaneous breakdown of neutral atoms to ions and electrons because of high temperature to maintain the discharge. This theory is covered in references 18 to 22 inclusive, and will not be considered further because it has been shown[1] that there are several important objections to it that make the theory unsatisfactory. One of these is that it assumes thermal equilibrium between the neutral gas molecules, the ions, and the electrons in the region of the cathode drop, which is not at all justified.

A most interesting study of alternating current arc characteristics has recently been reported by Sommer[6] who has verified Ramberg's[32] classification of electrode materials for the alternating current arc into three groups. Group I is the carbon group consisting of C, Ca, Mg. and W which are entirely consistent with the thermionic theory of the arc. Group II, the copper group, consists of such materials as Cu, Hg, Ag, and Au which are inconsistent with the thermionic theory and which seem to follow the electrostatic field emission theory previously outlined. Group III is the iron group of Pt, Sn, Pb, Ni, Zn, Al, Fe, and Cd which have characteristics different from the other two. Sommer also studied the effect of pressures up to atmospheric and frequencies of 50, 500, 1000, and 8000 cycles per second upon the current at which the discharge changed from one type to another. He found that increasing the pressure reduced the current at which the discharge changed from a half cycle of pure glow discharge which was repeated continuously to one which started out as a glow but changed early in the half cycle to an arc, the effect being different for different electrode materials studied. Increasing the frequency reduced the current at which the discharge changed from a glow plus an arc to an arc and also had a small effect in reducing the current at which a pure glow discharge changed to a glow plus an arc.

Slepian and Ludwig[8] have shown that for the mercury arc the transition, or backfire as it is called in a rectifier, from a glow to an arc seems to be a random phenomenon. Thoma and Heer[7] in their studies of the glow discharge found that the transition from a glow to an arc depended upon the conditions of the electrode surface. Several other papers along this line, but of less importance, are listed in the Bibliography.

The research reported in this thesis --- which, incidentally, was started before the most interesting of the above cited papers were published --- was undertaken to see if the data obtained at low pressures for short arcs between various materials and in different gases could throw more light on the transition from a glow discharge to an arc.

APPARATUS AND EXPERIMENTAL PROCEDURE

The experimental apparatus shown in Fig. 1 was arranged especially for the study of alternating current arcs under gas pressures from a few millimeters of mercury to atmospheric. The electrode holders, Fig. 2, were mounted on a heavy glass plate and covered by a bell jar with suitable connections to the vacuum pumps and pressure gages by means of which the gas pressure was adjusted to the desired value prior to striking the arc. All the work was done with cylindrical electrodes of 6.4 mm. diameter, the arc occuring between their plane end surfaces. Only one gap setting was used which was 1 mm. It would be instructive to carry out the same tests for several gap settings but at this time it seemed advisable to eliminate as many variables as possible.

The circuit used is shown in Fig.3. R_1 is a high resistance which, when the circuit is energized, will prevent an arc from striking by limiting the current to a very small value; at low pressures this permitted a glow discharge to exist, but at pressures above 20 cm. of Hg no discharge would take place when this resistance was in the circuit. The relay which short circuits R_1 is connected to the circuit energizing the oscillograph shutter and was set to operate after the oscillograph had recorded approximately one cycle of the voltage impressed across the electrodes. Short circuiting R_1 applies almost the full transformer secondary voltage V_T across the gap and causes an immediate breakdown into an arc. R_2 was used to adjust the arc current, which was measured by the ammeter A. R_3 determined the amplitude of the swing of the G.E. magnetic oscillograph element; this resistance had a value of approximately 30000 ohms for most of the tests. All these resistances were water resistors. The power for the circuit was obtained from the regular 60 cycle mains of the Kellogg Radiation Laboratory. Two transformers were available, one a Molony with a rating of 2Kw, 220/2200 volt and the other a Westinghouse 10 Kw. 220/6600 volt. Using the above method of starting the arc limits the arc current to values under 40 amperes and most of the research was confined to values of current less than 15 amperes.

The arc was allowed to burn only long enough to complete the oscillogram, and frequent adjustments were made of the gap to insure the desired separation of the electrodes, at the same time cleaning the arcing surfaces. For pressures above 5 cm. of Hg no increase in pressure was observed after the arc had lasted the average time of 2 seconds.

The results for metal electrodes, graphite in air at 2200 volts, impurity tests, and copper-carbon tests were obtained entirely from oscillograms. It was found that in the other cases comparable results could be obtained by using the oscillograph as a vibration galvanometer; the reignition potential showing up very well on the screen giving a value which was always within 5% of that obtained by averaging the individual reignition potentials from an oscillogram. Test oscillograms were taken at frequent intervals to insure the reliability of the data. Oscillograms were taken of 550 different arc conditions, in addition to the large amount of data taken directly from the oscillograph screen.

The spark discharge curves which are included for reference purposes in most of the figures and which are summarized in Fig.41 were obtained by charging a 1/2 m.fd. condenser in parallel with the gap by means of a Kenetron and a 14000 volt transformer. The discharge voltage being measured by a carefully calibrated electrostatic voltmeter. The average of five breakdowns being taken as the best value. Variations from this average were less than 2%.

EXPERIMENTAL RESULTS

In this research a study has been made of the reignition of an arc between electrodes of various materials operating in several gases. The effect of current and gas pressure upon the characteristics of arcs between these materials was determined and the results presented in the figures which will shortly be considered in detail.

The study was confined entirely to the arc reignition potential which was taken to be the maximum value of voltage attained prior to the reignition of the arc. At low pressures it has been noted that the extinguishing potential was approximately that of the normal glow voltage which appeared before the arc started --- the normal cathode drop. The effect of pressure and current upon this part of the discharge was not determined because of the inability to obtain this voltage and the reignition voltage on the same oscillogram. Further work along this line would be valuable.

The electrode material was found to have a pronounced effect upon the reignition potential. This quantity varied from cycle to cycle depending upon the electrode material. For spectroscopic graphite the variation was less than 5%; for projector carbon it was as much as 50% and for metals it was often as much as 25%. Experimental points indicated on the curves are each the average of more than seven values and in most cases at least thirty five values were averaged.

Figs. 4 and 5 are typical oscillograms representing the drop in potential across an arc between graphite electrodes in air for eight values of air pressure. The r.m.s. arc current for each of these cases was kept constant at 1.5 amperes. Fig. 4 shows the voltage drop across the gap as a function of time for low pressures. It is to be noted that the voltage rises before the current reverses, to a value which is approximately that of the cathode drop of the normal glow discharge in each case recorded here. Before R_1 was shorted, at point A, a glow discharge was taking place between the electrodes. At a pressure of 1 cm. of Hg an arc did not strike each half cycle, but the voltage did drop in some cases, e.g. half cycle number 6, to a value intermediate between that of the arc and the normal cathode drop. The explanation for this behavior, which was noted on numerous occasions at low pressures, is not known. The graphite electrodes for this record were obtained from two different sources which accounts for the slight difference between individual characteristics, i.e. when either was the cathode; this will be discussed further under impurities. It should be noted that the reignition and extinguishing glow discharge duration is reduced as the gas pressure is increased. By comparing Figs. 4 and 5, it is seen that the duration of the preliminary glow at high pressures is too short to be recorded by a magnetic oscillograph; since the circuit is almost pure resistance, the voltage across the gap rises approximately as a sine wave to the reignition potential. The extinguishing voltage is not visible because of the change in calibration of the voltage element necessary to record the high reignition potential. The reignition potentials of Figs. 4 and 5 are remarkably uniform due to the fact that the electrodes were pure. The electrode which is cathode when the voltage is above the zero line was a spectroscopic electrode made by the National Carbon Company.

The oscillogram of Fig.6 shows the effect of current upon an arc occuring between opposite electrodes of copper and carbon for a pressure of 5.1 cm. of Hg. Copper is the cathode when the voltage is above the zero line. The reignition and extinguishing glow discharges of the copper cathode are seen to be of shorter duration as the current is increased, i.e. the arc starts sooner and persists longer for large currents than for small currents. For the carbon cathode the reigniting glow is of shorter duration than when the copper is the cathode under the same conditions. The arc characteristic depends to a considerable extent upon the material that is the cathode. This difference has been pointed out by Sommer[6]: however, the characteristics are not the same as if the opposite electrode was of the same material as the cathode, for the properties of the opposite electrode of an alternating current arc have an important effect upon either characteristic as will be seen later. A record of the copper-carbon is not given for high pressures, because then the only difference in the characteristics is in their magnitude.

The variation with gas pressure of the reignition potential of an arc between pure graphite electrodes in air is shown in Fig. 7. These electrodes were special spectroscopic carbons of the National Carbon

Co. which were made of specially purified graphite having considerably less than 0.001% ash. According to the manufacturer, examination of these carbons has shown the presence of silicon, calcium, magnesium, silver, and copper: but no carbon has shown more than two or three of these elements and sometimes only one. Two were found to exhibit only the lines of carbon. It will be seen that for currents below 12.8 amperes the reignition potential increases with increases in the air pressure and that lower currents have the highest reignition potential. The spark curve is approached by the reignition potential as the current approaches zero. For low currents and moderately low pressures the reignition potential is directly proportional to the pressure. At 12.8 amperes the reignition potential is independent of pressure above 10 cm. of Hg. and has a value of 550 volts. Further increases in the current cause a lowering of the reignition potential which then decreases with increasing pressure. In every case there is a definite reignition potential which is higher than the voltage required to maintain the arc. Values of the reignition potential for pressures below 10 cm. of Hg. and currents over 6.5 amperes were not considered sufficiently reliable to justify their inclusion in the results, because of the fact that at these low pressures further increases in the arc current caused the discharge to spread to the electrode holders themselves and would therefore distort the characteristic of the pure graphite. It seems highly probable that current has no effect on the reignition potential below 5 cm. of Hg. Data from Fig. 7 are presented in Fig. 8 so as to show the effect of current on the reignition potential for various pressures. In this figure and all that follow of the same variables, the value of voltage at current zero is taken as the spark voltage for that pressure. These curves show quite clearly how the spark voltage is approached as the current is reduced. There are three distinct regions of behavior indicated by these curves. The region between 10 and 15 amperes is a transition region, the curves all crossing at 12.8 amperes and reversing their order. This region is one in which the temperature of the incoming cathode is changing from playing a minor to a major part in the reignition of the arc. Curves for other pressures are consistent with the three presented and all curves cross at the same current.

The experiments discussed above under Figs. 7 and

8 were repeated using a transformer having a higher secondary voltage and the results are presented in Figs. 9, 10, and 11. In this case it was possible to extend the pressure range to 70 cm. of Hg. The curves are straight lines almost to the maximum pressure and are quite consistent. Curves E and G of Fig. 9 were extrapolated to zero pressure to indicate the voltage at which all curves intersected. The relation between the slope of the lines of Fig. 9 and the arc current is given in Fig. 10. This curve extended to zero slope gives 9.6 amperes as the current in this case at which the reignition potential is independent of pressure. The reignition potential for this condition is given by the relation $V = 375 + Ap$ where p is the pressure in cm. of Hg. and A is the slope given by Fig. 10 for any current in that range. Fig. 11 indicates the same characteristic as Fig. 8. The transition region is seen to begin at about 4 amperes by both Fig. 10 and Fig. 11 since the curvature reverses at this point for both relations. Fig. 11, indicates quite clearly that as the pressure becomes quite low the current becomes less and less a factor in arc reignition. Fig. 12 is presented for the purpose of indicating more clearly the effect of transformer

voltage upon the arc reignition. It is obvious that the general effect of current is the same in the two cases. The current at which the reignition potential is independent of pressure is reduced as the transformer voltage is raised; but its value is only slightly lower. The reignition potential is decreased throughout by increasing the transformer voltage.

The arc reignition characteristics for pure graphite in commercial nitrogen are given in Figs. 13 to 16 inclusive. These characteristics are exactly similar in form to those for air. The small variation of individual points from the best curve is especially noticable for these materials. Some of the points of Fig. 14 showing the dependence of the slope of the reignition potential-pressure curves upon arc current were obtained directly from Fig. 13 and the others from Fig.15 using the justified assumption of a linear relation between reignition potential and pressure. The results are seen to be very consistent. Using the value of slope A from Fig. 14, the reignition potential may be computed by the relation $V = 250 + Ap$. Figs. 14 and 15 indicate a transition region exactly as in the case of air; this time it starts at about 5 amperes. Fig. 16 shows that the characteristics are of the same form for higher transformer voltages.

The next gas studied with pure graphite electrodes was commercial oxygen, the reignition characteristics of which are presented in Fig. 17 and 18. The reignition potential-pressure relationship is linear. All the curves intersect at zero pressure at a value of 550 volts which is approximately double that of air and nitrogen. The dependence of the reignition potential upon current is different from that of air and nitrogen for the currents investigated. After 1.5 amperes the reignition potential decreases linearly with increasing current; there being no transition region in the current range studied.

The reignition characteristics of pure graphite in commercial carbon dioxide are shown in Figs. 19 to 23. Fig. 19 exhibits two important differences from the characteristics of air, nitrogen and oxygen. First, the curves do not intersect if extended to zero pressure, but the intersections are distributed between 525 and 575 volts. Second, the curves for

1,2, and 4 amperes are identical for part of the pressure range. Further, there is more curvature in these characteristics than in those of the other gases. In Fig. 20 it is seen that there is a transition region between about 4 and 6 amperes; there is, however, no crossing of the curves as in nitrogen and air. The same effects are noted for the higher transformer voltage of Figs. 21 and 22, there being no difference in the reignition potential for currents from 1 to 4 amperes. In Fig.22 the transition region is between 4 and 8.5 amperes --- a much more gradual change with current between the region of slight temperature effect and the one where a high temperature predominates in effecting reignition. The effect of transformer voltage upon the reignition potential is indicated in Fig. 23; increasing the applied voltage reduces the reignition potential and leaves the characteristic shape essentially the same.

In order to better exhibit the effect of current on the arc reignition characteristics of pure graphite, a set of comparison curves, Figs. 24 and 25, were drawn for the four gases studied. In Fig. 24 the reignition characteristics for the gases as a function of the pressure are shown for two currents. With the exception of nitrogen the order of decreasing reignition potential for the 1 ampere case is CO_2,O_2 and air. For the 8 ampere case the order is CO_2, O_2, N_2. For air and nitrogen at 45 cm. of Hg, Fig. 25, it is seen that the reignition potential of the nitrogen is higher than that of air for currents less than 7 amperes and less than air for currents greater than this. At 25 cm. of Hg this change occurs at 2.5 amperes. In each case the reignition potential of oxygen lies between the two. Thus the reignition potential of air is lower than those of its constituents in the low current region and higher in the high current region. Carbon dioxide is highest throughout at low pressures and for most of the high pressure regions.

When two different materials are used as electrodes in an alternating current arc, the reignition potential is different for the two half cycles and depends to a large extent on the material of the new cathode for a given current. The reignition characteristics of both copper and carbon in air when each is the cathode in the presence of the other are presented in Figs. 26 to 30. Conductor copper was used for this purpose. The carbon was the National Carbon Company's projector carbon, made from very pure lamp black having 0.02% ash. Very small quantities of impurities such as boron, iron, aluminum, manganese, calcium, and magnesium were reported by the manufacturer as being present. This is a relatively impure material and the reignition potentials were quite erratic, the variations being as much as 50% of the average. The curves of Fig.26 are for the average values of reignition potential when copper was the cathode. In Fig.27 both average and maximum values are given, and it is seen that for each the effect of current is quite small at low pressures. At constant pressure the average copper reignition potential is seen to be almost independent of the current for currents above 6 amperes. In the case where carbon is the cathode, Figs. 28 and 29, it is seen that a very low reignition potential is reached at about 6 amperes which is also almost independent of current. It will be noted, Figs. 29 and 30, that when carbon is the cathode there is for each current a pressure at which the reignition potential is a maximum. When copper is the cathode this effect is not observed. In Fig. 30 a curve for pure graphite in air is included for comparison. The fact that this curve is above the corresponding one for copper indicates that the opposite, somewhat impure carbon, has influenced the copper characteristic to a considerable extent even at this low current.

The influence of current on the reignition potentials of metals in air at atmospheric pressure was determined for copper, aluminum, cadmium, zinc, and carbon steel; the characteristics of which, except for zinc, are presented in Figs. 31 to 35. All values for these materials were obtained from oscillograms and the average values of 40 to 50 individual reignition potentials are indicated by the points. The electrodes were cleaned of oxide and pits and the gap readjusted between each record. The maximum and minimum values found on the oscillogram of each current are given to show the greatest variation from the average. It is interesting to note that the curves of maximum, average, and minimum reignition potentials are all of the same form, and that the points are quite consistent. The values of reignition potentials obtained from oscillograms when zinc was used were so erratic that it was impossible to determine a curve showing the effect of current. This variation may be due to impurities in the zinc or to the effect of zinc oxide. Current is most effective in reducing the reignition potential when it is less than 5 amperes. That the opposite carbon of the copper-carbon arc has a considerable effect in lowering the copper reignition potential is evident upon comparing the values of Fig.31 with those of Fig. 27 at 70 cm. of Hg for corresponding currents. The various metal characteristics are compared with that of graphite in Fig. 36. It is evident from these curves that the effect of current on graphite is exactly like that of a metal until a current of 4 amperes is reached when the temperature of the cathode for graphite can continue to increase while the temperature of the metal is limited by its boiling point, reached at about the same current. It should be noted that the reignition potential of copper does not approach a constant value within the current range studied as was the case with the other metals. This may be due to the low work function of CuO which is inevitably present when the arc is in the air.

Oscillograms were taken to determine the effect of impurities upon the reignition potentials and are summarized in Fig. 36. The results of using a carbon which was impregnated with a fair quantity of sodium hydroxide as one electrode and an untreated carbon of the same stock are indicated by curves F, G, H, and I. The reignition potentials of both the treated and untreated electrodes were very markedly reduced from the corresponding values when the untreated electrode was run against copper. Curves D and E are for pure graphite as one electrode and the other a carbon made by the National Carbon Company for use in flaming arc lamps. The latter carbon contained about 35% ash, consisting of 15% of the rare earths, cerium, neodymium, and lanthanium, and 20% calcium fluride. It is important to note that not only is the reignition potential of the impure electrode lowered from its pure characteristic but that also the opposite pure electrode has its reignition potential lowered almost as much as the impure one.

In order to indicate the effect of another physical property of electrode materials upon arc reignition the curves of Fig. 37 were plotted showing the influence of the coefficient of heat conductivity of the electrode upon the reignition potential. As the current is increased the low coefficients of carbon and graphite have a pronounced effect upon the reignition potential. The values for copper were taken from the maximum curves of the copper-carbon arc.

Both pressure and current may be seen to have an effect on the reignition potential through their effect on the cathode temperature by considering the photographs of the arc, Fig. 38, for two currents and three pressures. For low pressures the apparent cathode area is poorly defined and extends over a very large area which is increased as in (b) and (c). As the pressure is increased this apparent cathode area decreases and at high pressures it is confined to the plane end surfaces of the electrodes. It is evident that for a given current, more energy is being put into unit cathode area at high pressures than at low pressures and consequently a high cathode temperature is produced.

Another factor influencing arc reignition is the rate of rise of the impressed voltage at current zero. In a resistance circuit as was used in this work the rate of rise of impressed voltage may be varied by changing the transformer voltage or by changing the frequency. The first method was most successful in this case and the results for a graphite arc in nitrogen are presented in Figs. 39 and 40. The spark voltage is indicated as the point at zero dV/dt, this is not strictly correct, of course, but it is satisfactory for the purpose of plotting since the rate of rise of the D.C. voltage used in obtaining the spark characteristic was very small compared to that of the reignition of the arc. Increasing the frequency was also found to decrease the reignition voltage. Increasing the rate of rise of applied voltage is seen to be less effective in lowering the reignition potential at low pressures than it is at the higher pressures.

A summary of the materials studied for air at 70 cm. of Hg and currents greater than 4 amperes is given in Table I with certain of their physical constants which may affect arc reignition. It is seen that except for steel, decreasing coefficient of heat conductivity is accompanied by a decrease in the reignition potential. The same is true for the specific heat except for graphite. Both factors tend to make a given current more effective in raising the temperature of the active portion of the electrode. The thermionic constants indicate cause for variation in the reignition potentials of metals as does also the work function. In some cases the work function of the metal is greater and in others it is less than that of the oxide which is constantly being formed. Since the temperature of cadmium is limited to a value where the effect of temperature on field currents is small, it is probable that its oxide is very active, because of its low work function, in lowering the reignition potential.

In Table II a summary is made of the effect of the four gases on the reignition potential of graphite, together with some of their physical constants. There is a positive correlation between reignition potential and the coefficient of recombination and the mobility of the gas ions. The specific heat relation is such as to raise the reignition potential instead of lower it; but it is probable that this factor plays a very small part. The relation between the reignition potential and the number of ion pairs produced by a negative ion in one centimeter of drift is the opposite of that which would be expected. The reignition potential and the cathode drop are similarly affected by the gases, indicating related phenomena. The ionizing potentials do not indicate an explanation of the variation of the reignition potential.

Since the arc is a very complex phenomenon, the properties listed in Tables I and II are those which could have some effect upon the arc reignition. The actual value of the reignition potential is quite probably due to all these factors acting at the same time. Under certain conditions of pressure and current some factors will predominate and under different conditions other factors will be controlling.

DISCUSSION OF RESULTS

At the values of pressure, current and frequency at which this work was done the reignition potential would be approximately the same as the sparking potential of the gas used if the characteristics of the electrodes did not change during the discharge. This is true because the time required for all the ions and electrons of a short arc to recombine is extremely short[13] and since the circuit being used was almost pure resistance, the voltage across the gap increased as a sine wave at a relatively slow rate, allowing a large dionization of the gap to take place. There may be some slight effect due to an increase in the average temperature of the gas; but large deviations of the reignition potential from the sparking potential such as have been shown to occur by the experimental results must be explained by changes in the properties of the electrodes, and particularly in that electrode which is to become the cathode. Only those changes need be considered which would effect the number of electrons emitted by the cathode or the ease with which they might be emitted by the high intensity electric field produced by the positive ion sheath constituting the cathode drop region. The only factors would seem to be the temperature of that portion of the electrode which emits electrons and the presence of electropositive materials which have low work functions.

At high electrode temperatures the electric field necessary to produce sufficient electrons to maintain the arc is reduced. If the temperature of the electrode is high enough a sufficient number of electrons may be emitted by thermionic action to reignite the arc with a voltage no higher than that required to maintain it. This latter condition did not obtain in any of the cases presented in this paper since in all cases a reignition potential was necessary. At the higher pressures and at the higher currents with carbon and graphite electrodes this potential was not high. It is believed that in these cases the electrodes were hot enough to emit a considerable thermionic current from the active spot; though not sufficient electrons in number for the large current density known to exist at the cathode spot, namely a density of the order of a thousand amperes per square centimeter. When the reignition potential is relatively low, as in the transition region where it is decreasing rapidly with increased current, sufficient electrons to maintain the arc are probably produced by a combination of high temperature and high electric field. It is interesting to note that at the low values of current, i.e. less than 4 amperes, and also for low pressures, the reignition potentials for carbon and graphite are of the same order of magnitude as those of the metals and further that the effect of increasing the current in this region, i.e. the shape of the reignition potential-current curves, is the same for all materials studied. Here the temperature of the active spot is too low to play any essential part, and the restriking of the arc is largely due to the electric field of high intensity that exists there. It is important to note that the arc current has a very definite, though relatively small, effect upon the reignition potentials of metals; this effect does not continue for large currents because the electrode temperature is limited in this case by the boiling point of the metal ---

a limit which is not placed upon carbon and graphite.

It is well known that field currents due to high intensity electric fields are independent of the temperature of the electrodes until their temperature exceeds about 1000°K[3]. Consequently it is only at temperatures higher than this that any marked difference between the reignition potential and the sparking potential would be expected. If the temperature is lower than this any difference between the sparking potential and the reignition potential might be due to a greater number of ions and electrons remaining in the space between the electrodes, because of a previous arc current, when the arc is restruck. The fact that the reignition potential does not decrease with an increase of the average temperature of the electrode, i.e. it is not noticeably lower after ten half cycles than after the first half cycle, is in accord with the independence of the field current and temperature, providing the temperature is low.

On the other hand anything that either increases the temperature of the cathode spot or anything that decreases the cooling while that electrode is anode and during the period of zero current, is found to decrease the reignition potential. Thus both an increase in current and an increase in pressure cause a greater difference between the reignition potential and the sparking potential because both increase the temperature of the cathode spot. Increasing the pressure increases the temperature of the cathode spot because the size of the cathode spot decreases as the pressure increases and consequently the current density to the cathode spot is increased. Increasing the initial rate of rise of voltage across the gap and increasing the frequency of the applied voltage have been found to decrease the reignition potential because both allow less time for the cathode spot to cool and also less time is available for deionization of the gap. In the same way it is found that a higher coefficient of heat conductivity and a higher specific heat of the electrode is, in general, accompanied by a higher reignition potential; the former causing greater cooling and the latter requiring more energy input for a given temperature. It is believed that the reason the reignition potentials are in the order given in Table I and Fig. 37 is due to a considerable extent to the fact that the electrode specific heats and coefficients of heat conductivity are in the same order; with two exceptions, where other factors are obviously more important than these.

Materials which have a low work function will emit electrons much more readily than those with a high work function, consequently if there is in the electrode an impurity such as one of the alkali earths, which have a much lower value of work function than the electrode material itself, one would expect that the reignition potential would be much lower than in the case of a pure electrode. The experimental results show that this is true. The results also show that the amount of such impurity need be very small to affect the reignition greatly, since if a pure material is used as one electrode its reignition potential is decreased nearly as much as that of the electrode having the impurity in it and has the opposite polarity. Since material is being continuously vaporized from the surface of both electrodes, there can be no accumulation of impurities on the pure electrode. A trace of impurity such as the alkali metals in a relatively pure electrode can account for the random variations of the reignition potential. The reignition potential would be low if a trace of alkali metal happened to be on the surface of the electrode becoming the cathode. The difference in work function of metals and their oxides would produce variations in the reignition potential in addition to the ever present impurities, when these materials are used in air.

The effect of gases upon the reignition of an arc is very complex. Some of the properties of gases which could influence reignition have been listed in Table II. The effect of chemical processes occuring in the arc region is not known; but quite probably enters to a considerable extent. Two well known effects of gases on thermionic emission[5] are, first, the formation of an adsorbed monomolecular or monatomic film on the surface; second, positive ions are formed which sputter atoms off the emitting surface and may affect emission considerably. In general an adsorbed gas layer decreases electron emission; but in the case of carbon and oxygen the effect is the opposite. In conjunction with other properties, the ionization potential of the gas and the properties of its ions will affect the reignition potential just as they affect either the deionization of the gap or the formation of the positive ion sheath of the cathode drop.

All the experimental facts are in accord with the following theory of the transition from the glow discharge to an arc which has been proposed by Dr. S.S. Mackeown[1]. When the current reverses a glow discharge is first formed with the relatively high cathode drop. As the current density at the cathode increases in the region of the abnormal cathode drop, the magnitude of the cathode drop increases and also this cathode drop occurs in a region which is closer to the cathode. Both of these effects cause an increase in the intensity of the electric field existing in the cathode drop and consequently increase the energy that the positive ions have when they hit the cathode. As the energy of the positive ions increases they produce a larger number of electrons from the cathode by bombardment. If now some impurity is assumed on the surface of the cathode or some irregularity that produces a high intensity local electric field, then that portion of the cathode will produce a larger number of electrons than any other part of the cathode. The electrons freed from the cathode will produce ionization which will be more intense near the active spot on the cathode surface. Due to the high mobility of the electrons compared to the positive ions the former will disperse into the body of the gas leaving behind the positively charged gas ions. This will further increase the field near the active surface of the cathode with a corresponding increase in the number of electrons emitted from that spot. This process is cumulative and proceeds rapidly until the electric field existing at this active spot is high enough to pull large numbers of electrons from the cathode surface. When this occurs an arc exists with its characteristic "hot spot" with a very high current density and with a low cathode drop. A high temperature at the cathode will decrease the magnitude of the electric field necessary to produce these electrons.

CONCLUSIONS

1. The reignition potentials of all materials studied are affected the same by currents from 0 to 4 amperes. For higher currents the difference between the reignition potentials of carbon and graphite, and those of the metals is very great.

2. At low pressures a reignition potential that is high compared to the arc voltage is necessary to establish the arc even when the electrodes are carbon.

3. All factors tending to cool the electrodes increase the reignition potential.

4. The reignition potential is a function of the condition of the surface of the electrodes and may be decreased markedly by minute traces of impurities of low work function materials such as the alkali metals.

5. The experimental results are consistent with the theory that the transition from a glow discharge to an arc is due to the establishment of a high positive space charge at the surface of the cathode producing an electric field of high intensity which draws out large numbers of electrons from the cathode surface.

ACKNOWLEDGMENT

I wish to express my appreciation of the valuable advice and inspiration received from Dr. S.S. Mackeown throughout this work. I am also indebted to the National Carbon Company's Research Laboratory for the donation of special materials, without which some of the most valuable results could not have been obtained.

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BIBLIOGRAPHY

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FIGURES

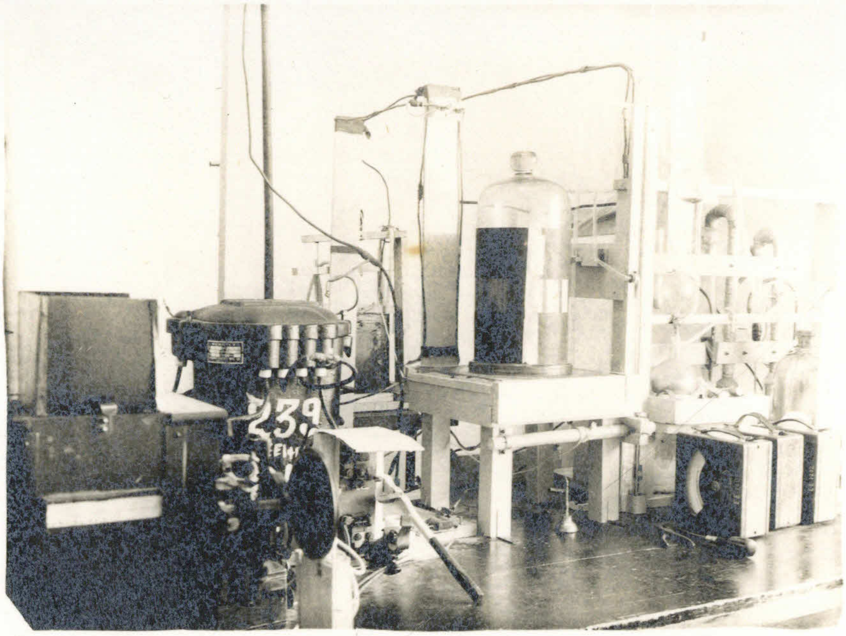


Fig. 1

LABORATORY

404 Kellogg Radiation Laboratory

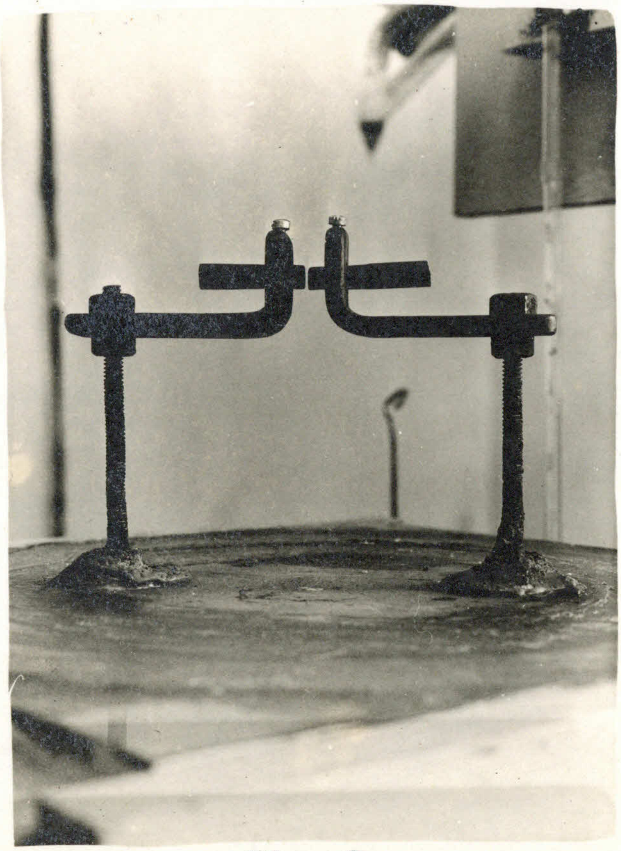


Fig. 2

ELECTRODE MOUNTINGS

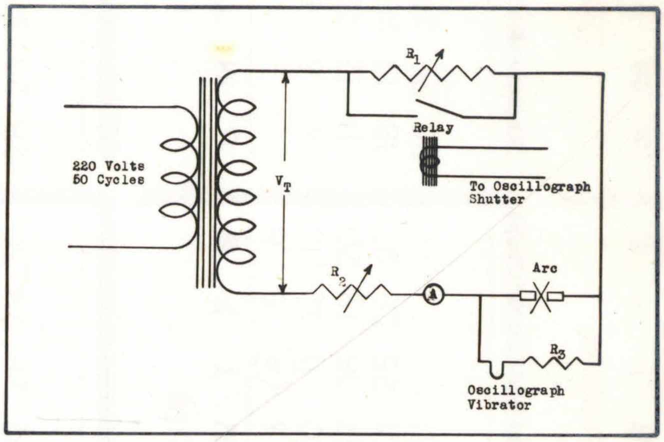


Fig. 3
EXPERIMENTAL CIRCUIT

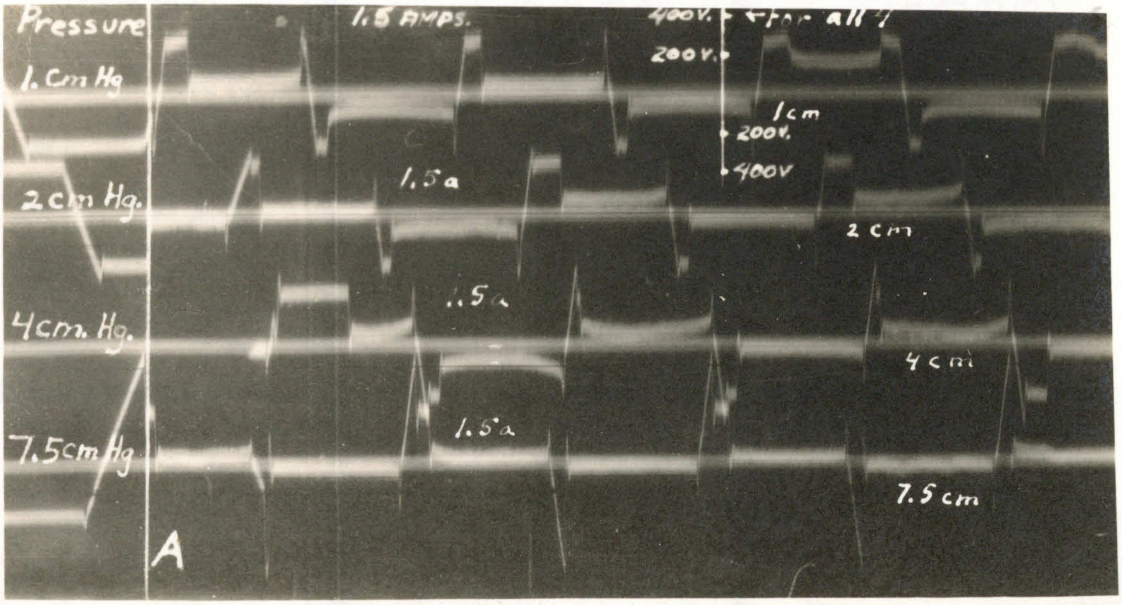


Fig. 4
OSCILLOGRAM OF ARC BETWEEN PURE GRAPHITE ELECTRODES
IN AIR
Voltage Scale is the Same for Each Pressure
The Arc Starts at A

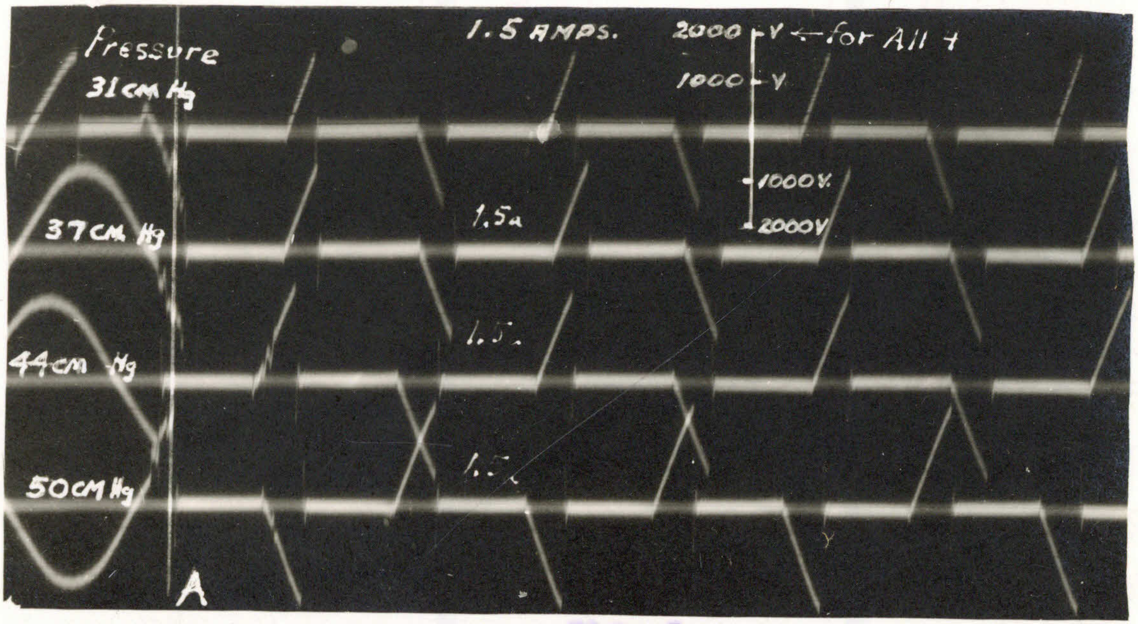


Fig. 5
OSCILLOGRAM OF ARC BETWEEN PURE GRAPHITE ELECTRODES
IN AIR
Voltage Scale is the Same for Each Pressure
The Arc Starts at A

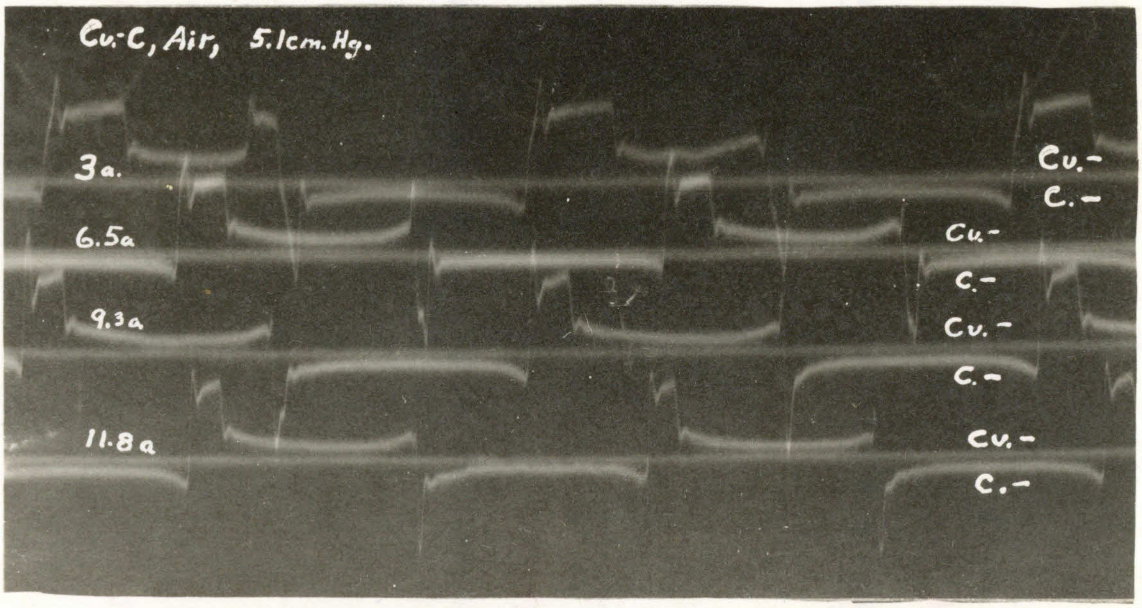


Fig. 6
OSCILLOGRAM SHOWING EFFECT OF CURRENT
ON
COPPER -CARBON ARC IN AIR

(Voltage Record)

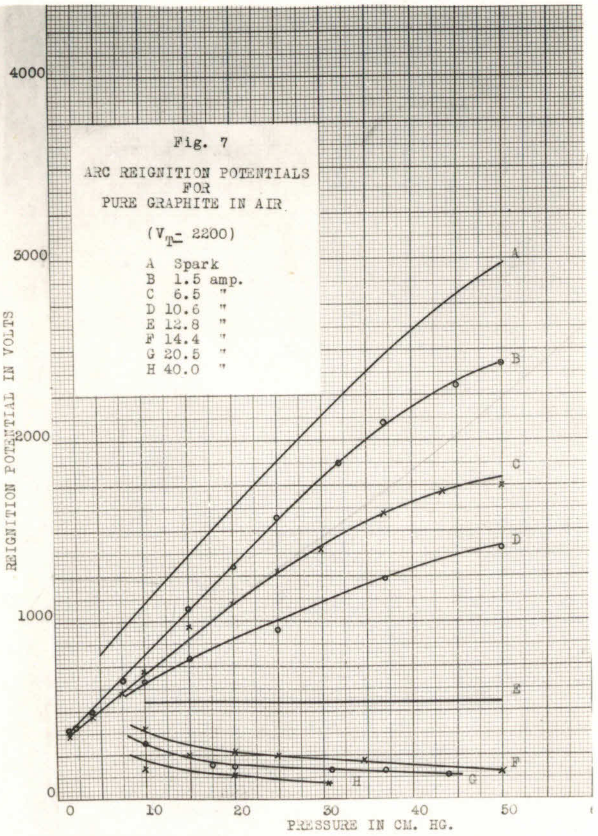


Fig. 7

ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE IN AIR

(V_T = 2200)

A	Spark
B	1.5 amp.
C	6.5 "
D	10.6 "
E	12.8 "
F	14.4 "
G	20.5 "
H	40.0 "

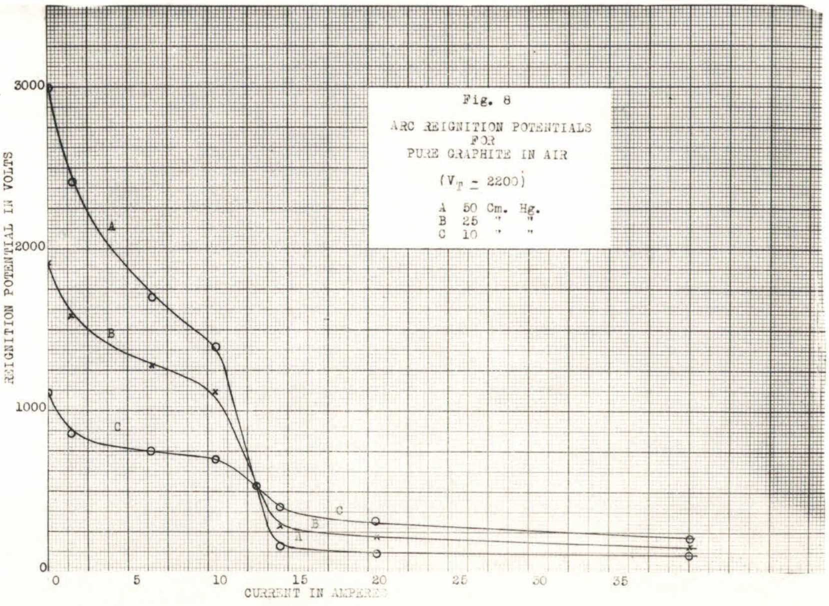


Fig. 8

ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE IN AIR

(V_T = 2200)

A	50 Cm. Hg.
B	25 " "
C	10 " "

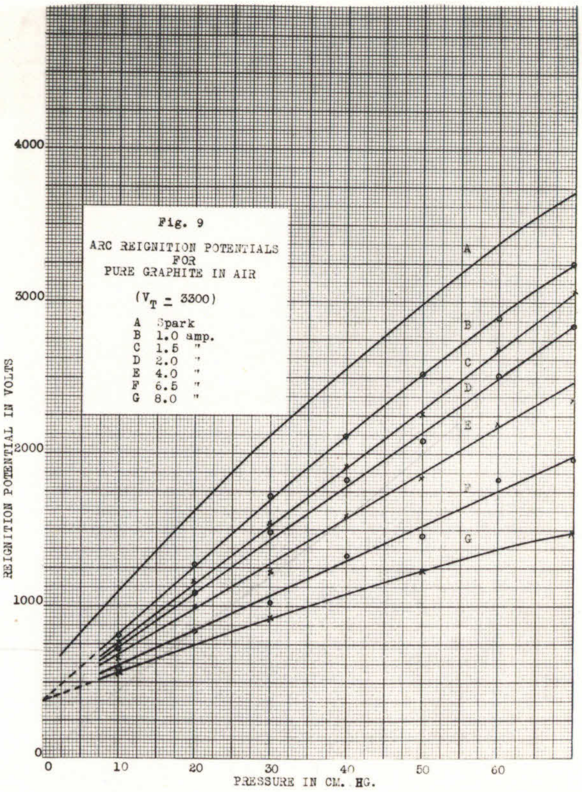


Fig. 9

ARC REIGNITION POTENTIALS FOR PURE GRAPHITE IN AIR

($V_T = 3300$)

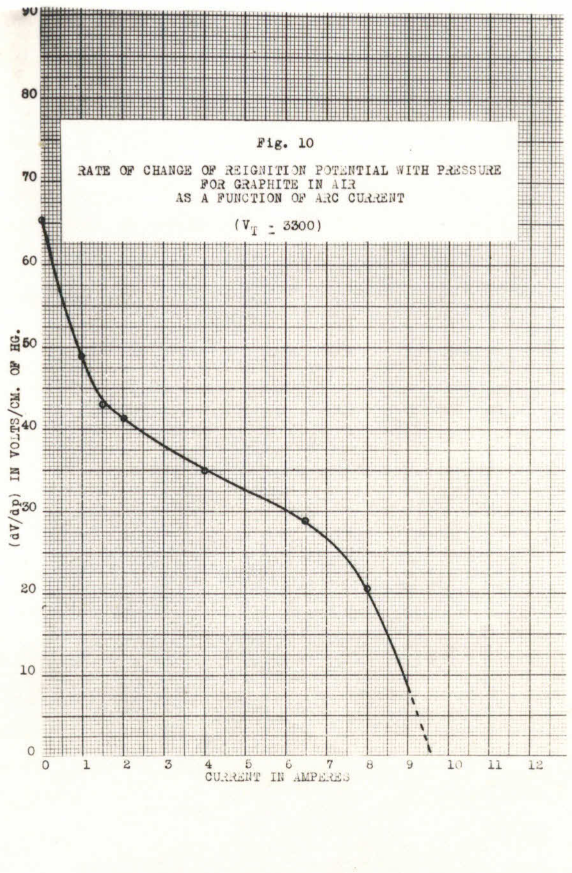


Fig. 10

RATE OF CHANGE OF REIGNITION POTENTIAL WITH PRESSURE FOR GRAPHITE IN AIR AS A FUNCTION OF ARC CURRENT

($V_T = 3300$)

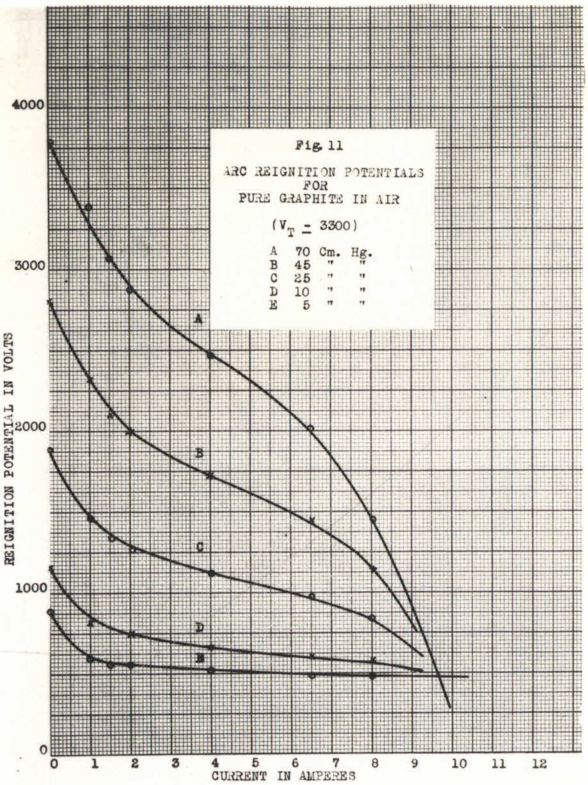


Fig. 11

ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE IN AIR

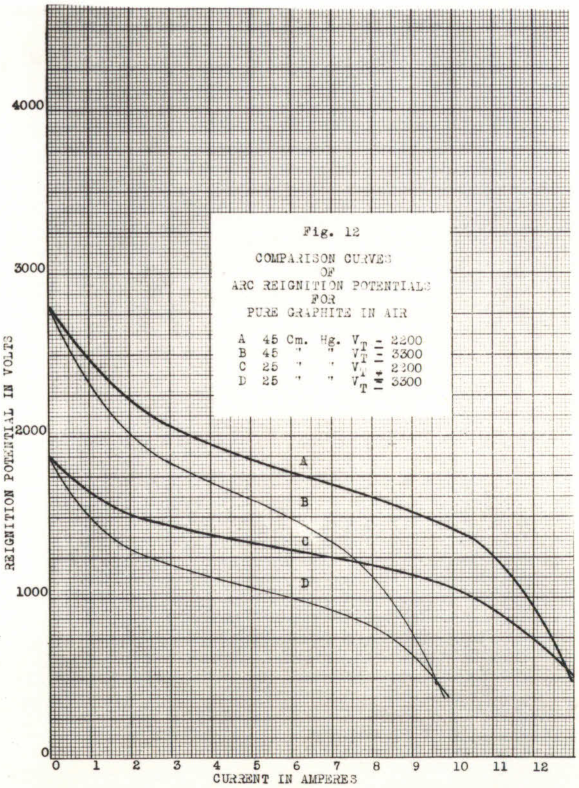


Fig. 12

COMPARISON CURVES
OF
ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE IN AIR

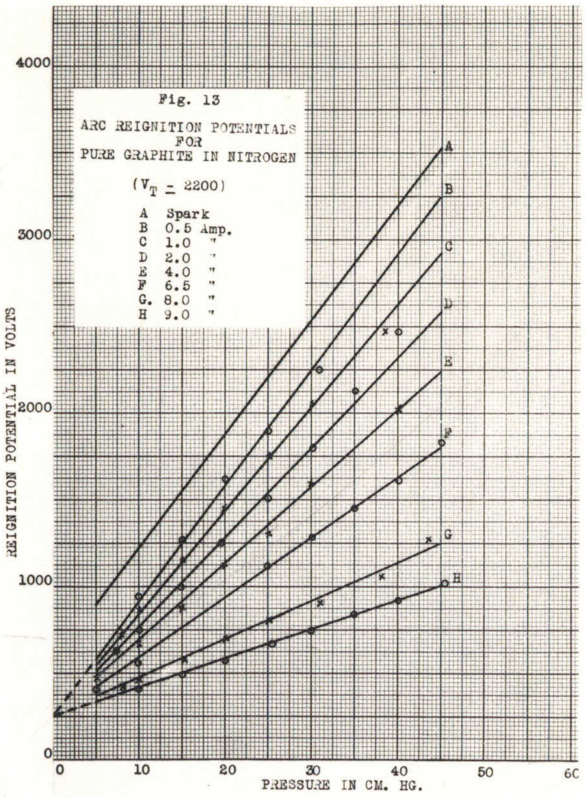


Fig. 13

ARC REIGNITION POTENTIALS FOR PURE GRAPHITE IN NITROGEN

($V_T = 2200$)

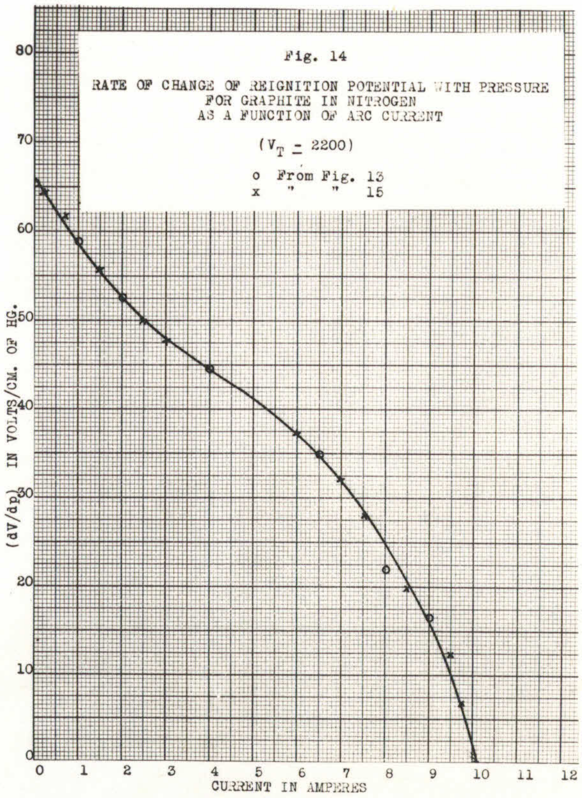


Fig. 14

RATE OF CHANGE OF REIGNITION POTENTIAL WITH PRESSURE FOR GRAPHITE IN NITROGEN AS A FUNCTION OF ARC CURRENT

($V_T = 2200$)

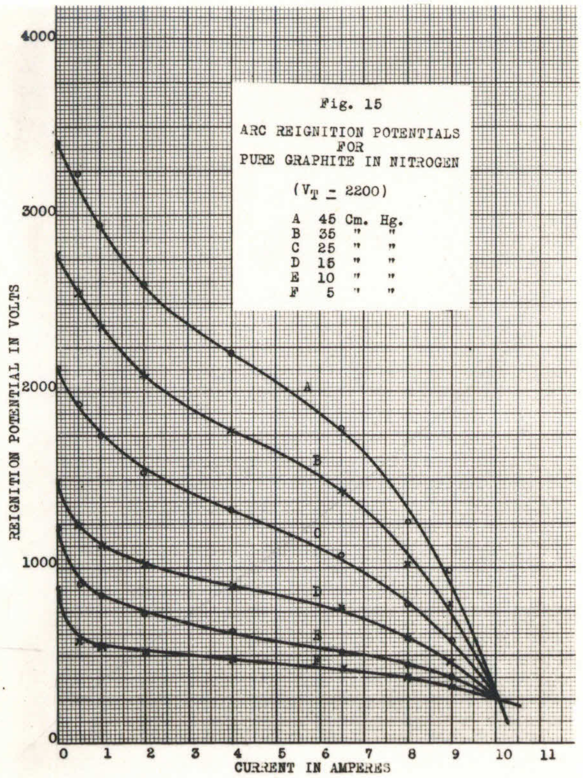


Fig. 15

ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE IN NITROGEN

(V_T = 2200)

A 45 Cm. Hg.
B 35 " "
C 25 " "
D 15 " "
E 10 " "
F 5 " "

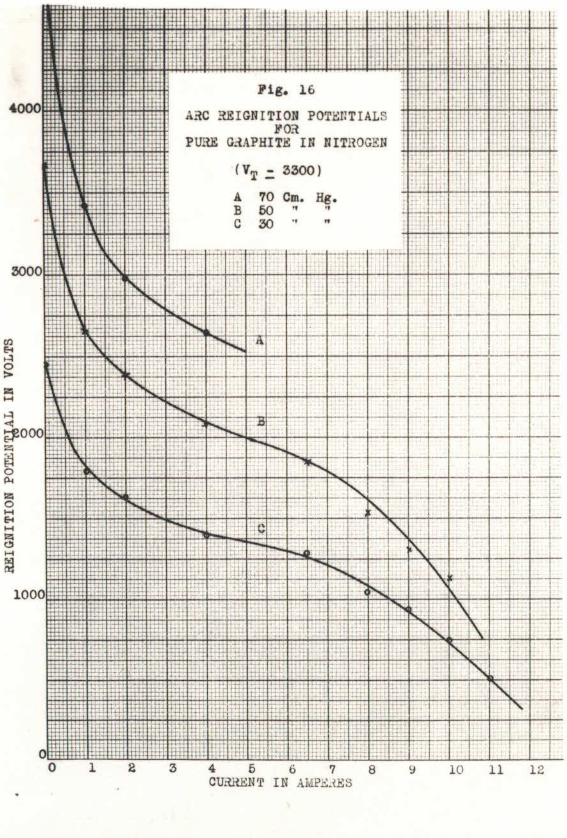


Fig. 16

ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE IN NITROGEN

(V_T = 3300)

A 70 Cm. Hg.
B 50 " "
C 30 " "

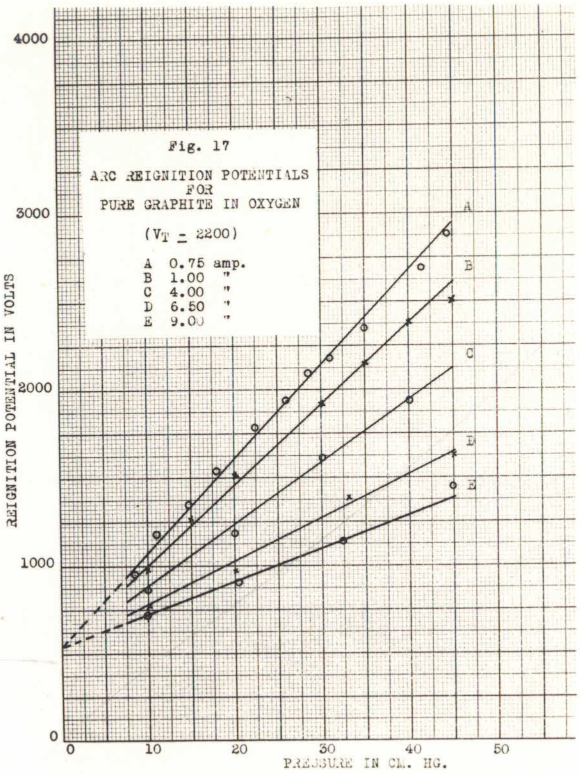


Fig. 17

ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE IN OXYGEN

(V_T = 2200)

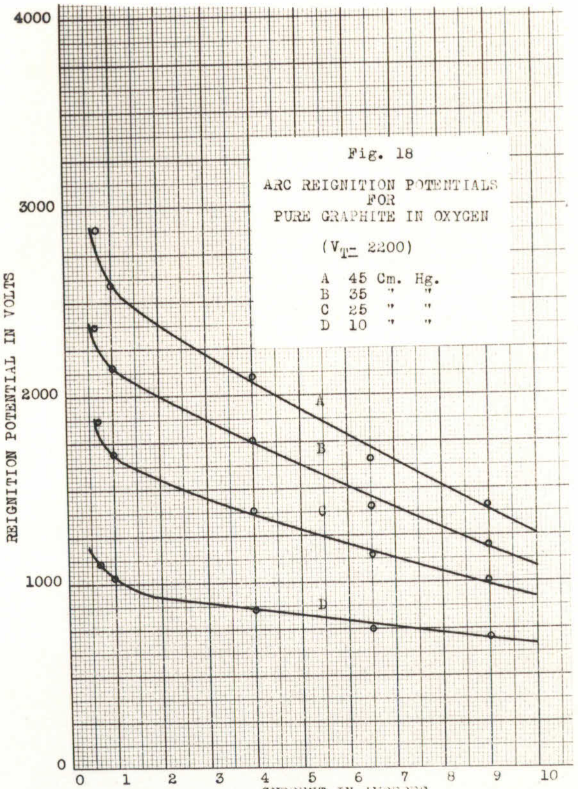


Fig. 18

ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE IN OXYGEN

(V_T = 2200)

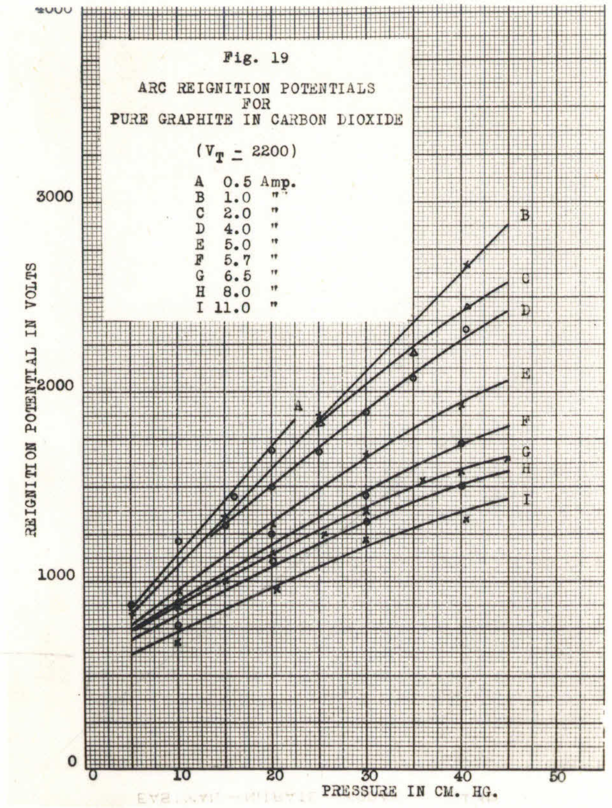


Fig. 19

ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE IN CARBON DIOXIDE

(V_T = 2200)

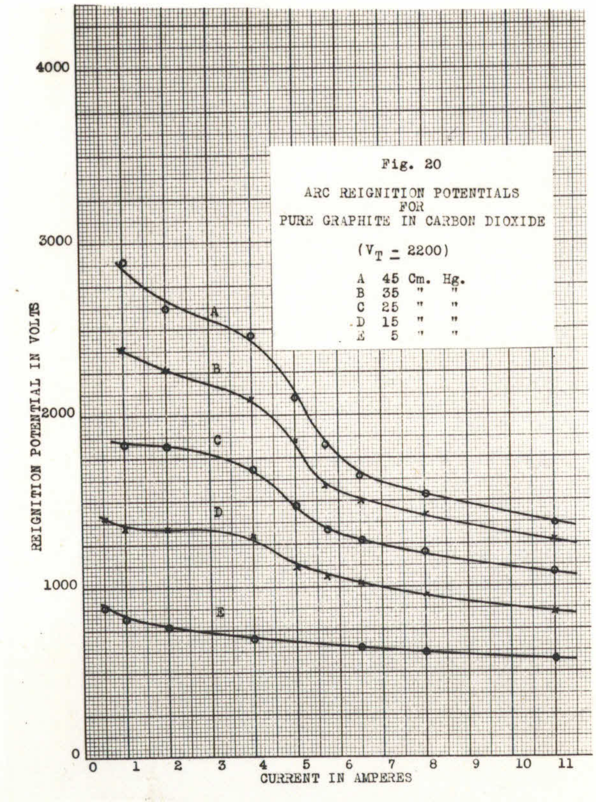


Fig. 20

ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE IN CARBON DIOXIDE

(V_T = 2200)

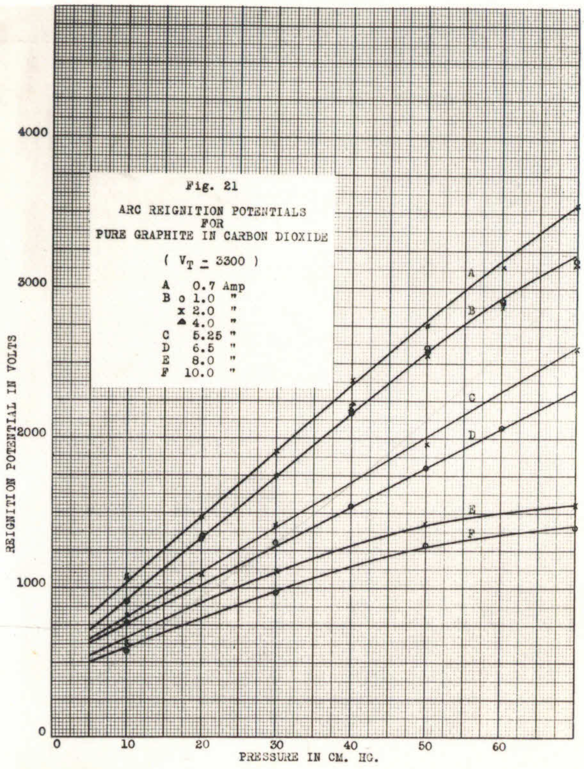


Fig. 21

ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE IN CARBON DIOXIDE

($V_T = 3300$)

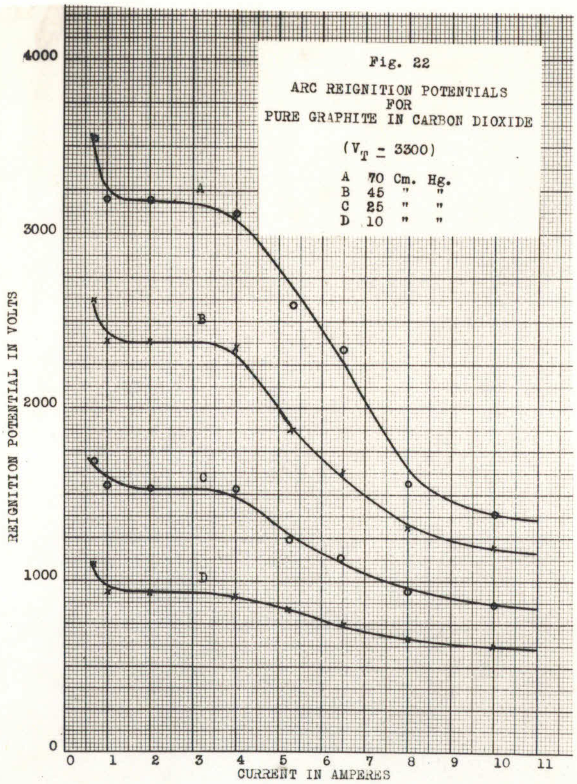


Fig. 22

ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE IN CARBON DIOXIDE

($V_T = 3300$)

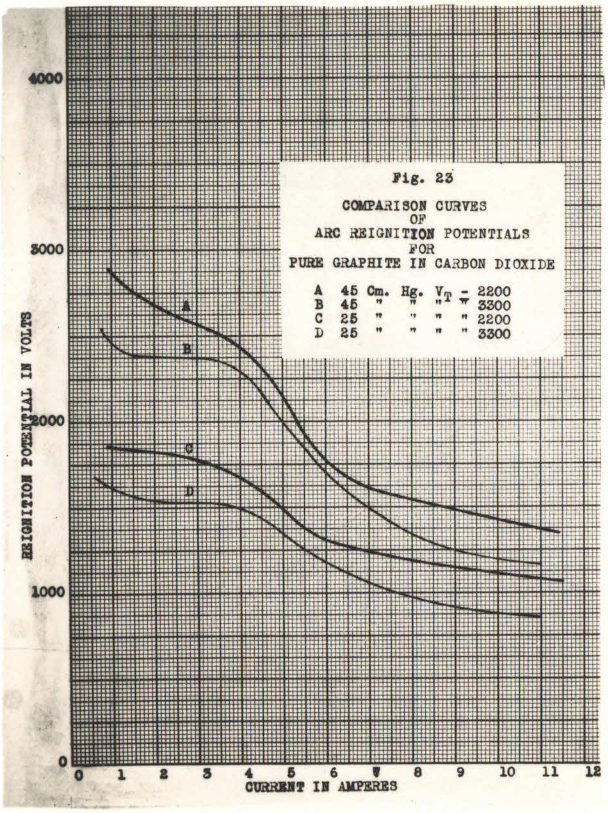


Fig. 23

COMPARISON CURVES OF ARC REIGNITION POTENTIALS FOR PURE GRAPHITE IN CARBON DIOXIDE

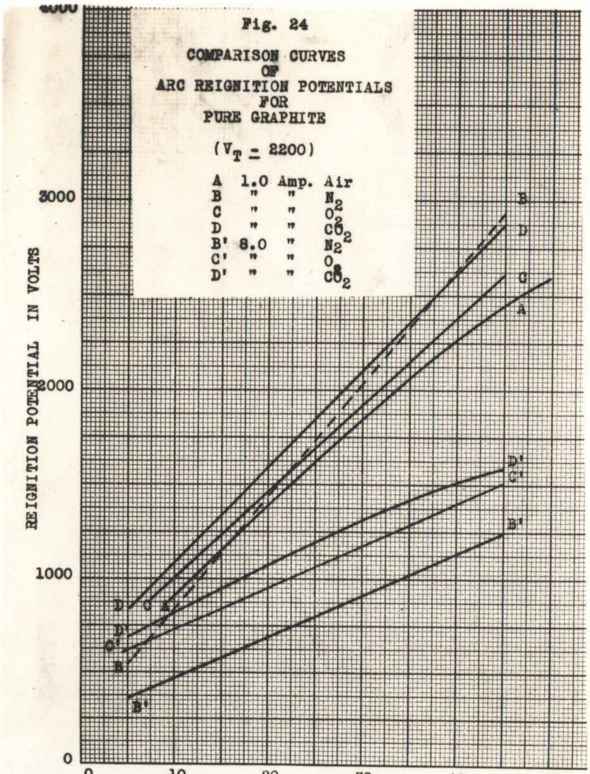


Fig. 24

COMPARISON CURVES OF ARC REIGNITION POTENTIALS FOR PURE GRAPHITE

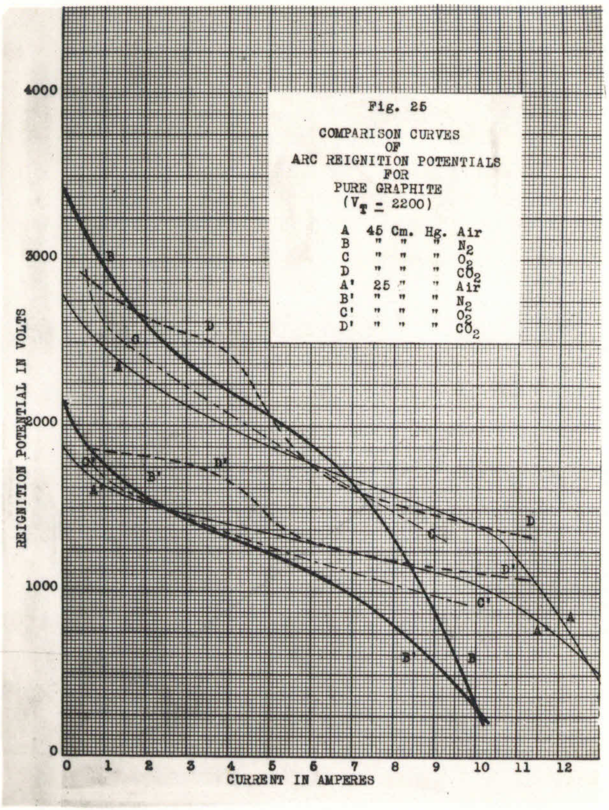


Fig. 25

COMPARISON CURVES
OF
ARC REIGNITION POTENTIALS
FOR
PURE GRAPHITE
($V_T = 2200$)

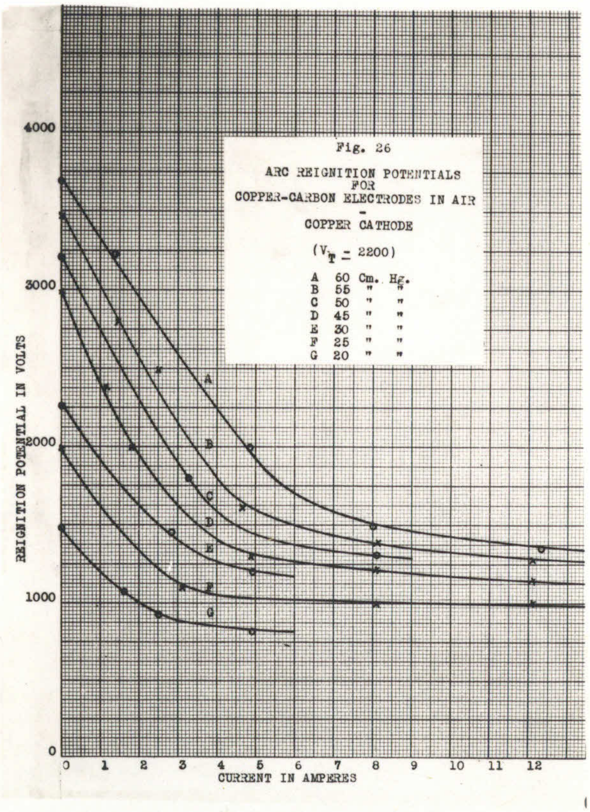


Fig. 26

ARC REIGNITION POTENTIALS
FOR
COPPER-CARBON ELECTRODES IN AIR
-
COPPER CATHODE

($V_T = 2200$)

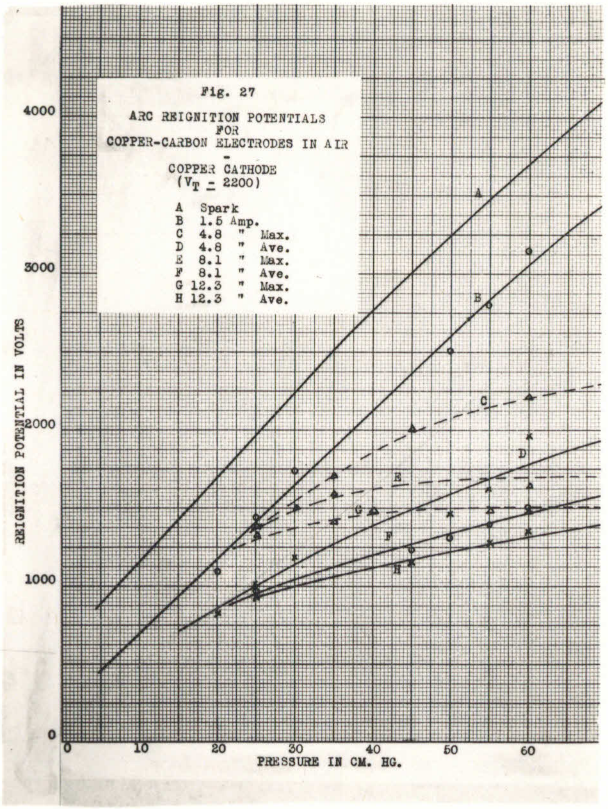


Fig. 27

ARC REIGNITION POTENTIALS FOR COPPER-CARBON ELECTRODES IN AIR

-

COPPER CATHODE

(V_T = 2200)

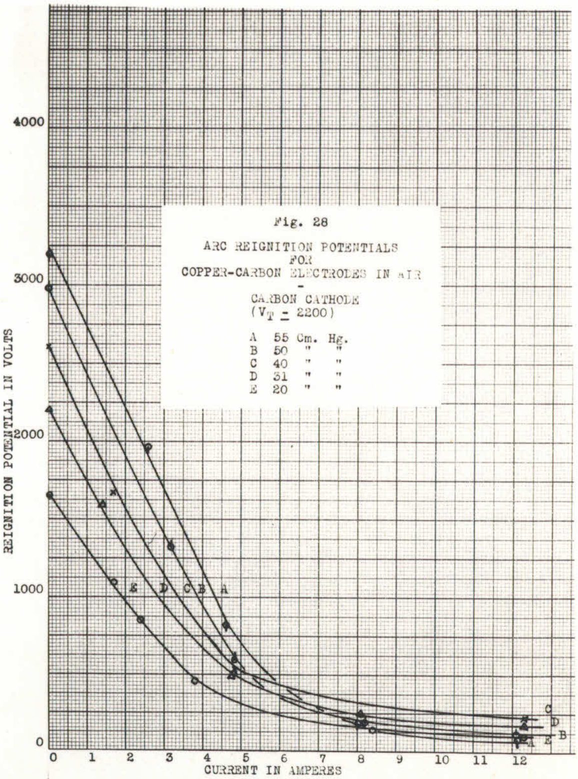


Fig. 28

ARC REIGNITION POTENTIALS FOR COPPER-CARBON ELECTRODES IN AIR

-

CARBON CATHODE

(V_T = 2200)

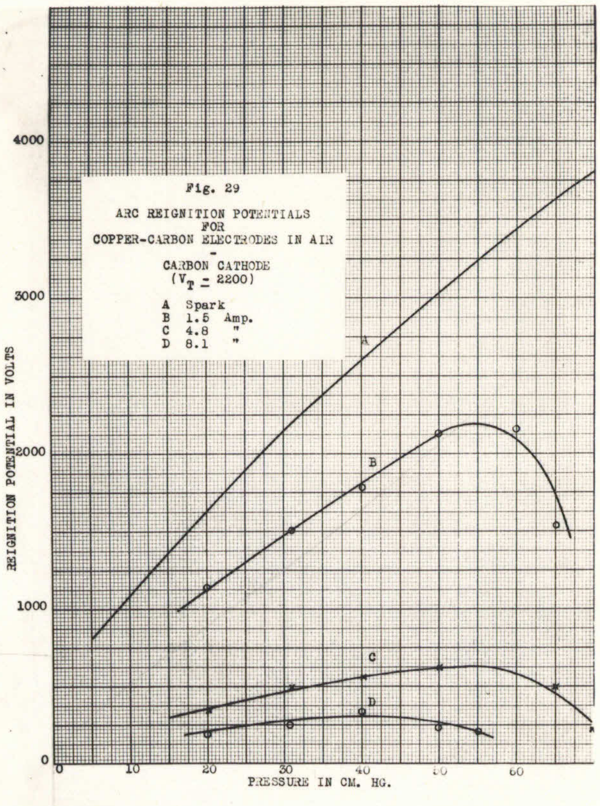


Fig. 29

ARC REIGNITION POTENTIALS
FOR
COPPER-CARBON ELECTRODES IN AIR
-
CARBON CATHODE
($V_T = 2200$)

A Spark
B 1.5 Amp.
C 4.8 "
D 8.1 "

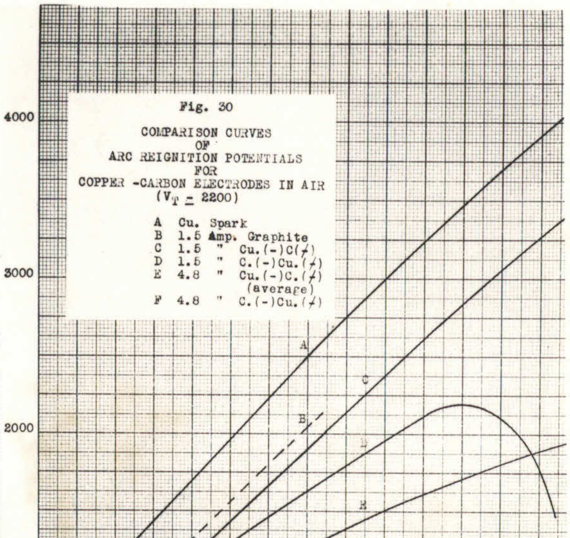


Fig. 30

COMPARISON CURVES
OF
ARC REIGNITION POTENTIALS
FOR
COPPER -CARBON ELECTRODES IN AIR
($V_T = 2200$)

A Cu. Spark
B 1.5 Amp. Graphite
C 1.5 " Cu.(-)C(+)
D 1.5 " C.(-)Cu.(+)
E 4.8 " Cu.(-)C.(+) (average)
F 4.8 " C.(-)Cu.(+)

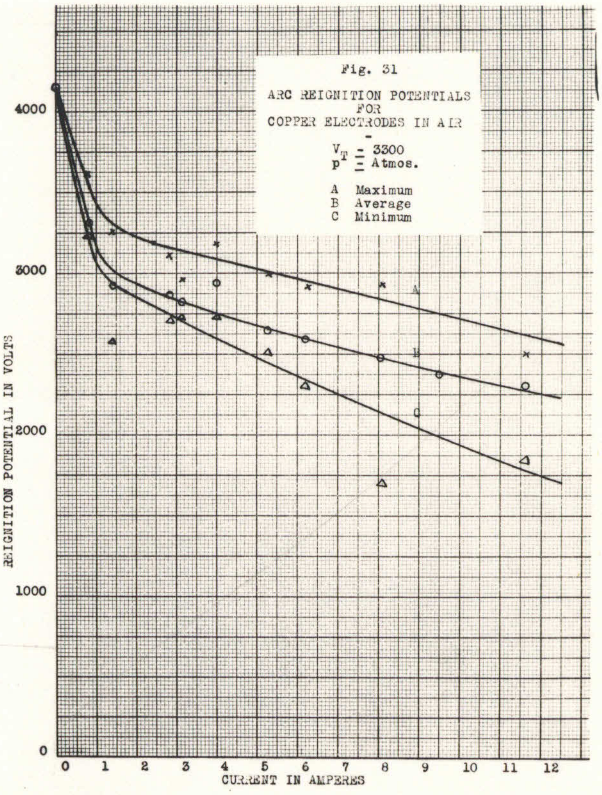


Fig. 31

ARC REIGNITION POTENTIALS
FOR
COPPER ELECTRODES IN AIR
-
$V_T = 3300$
$p = $ Atmos.

A Maximum
B Average
C Minimum

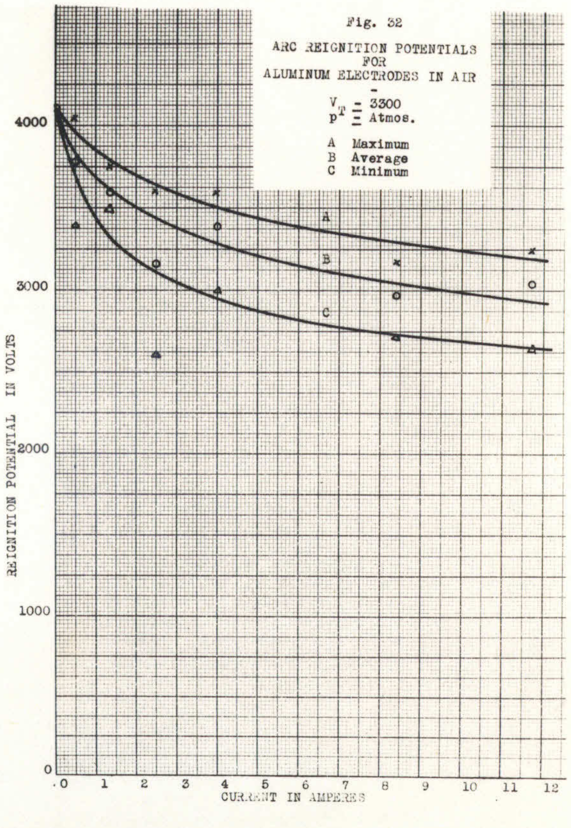


Fig. 32

ARC REIGNITION POTENTIALS
FOR
ALUMINUM ELECTRODES IN AIR
-
$V_T = 3300$
$p = $ Atmos.

A Maximum
B Average
C Minimum

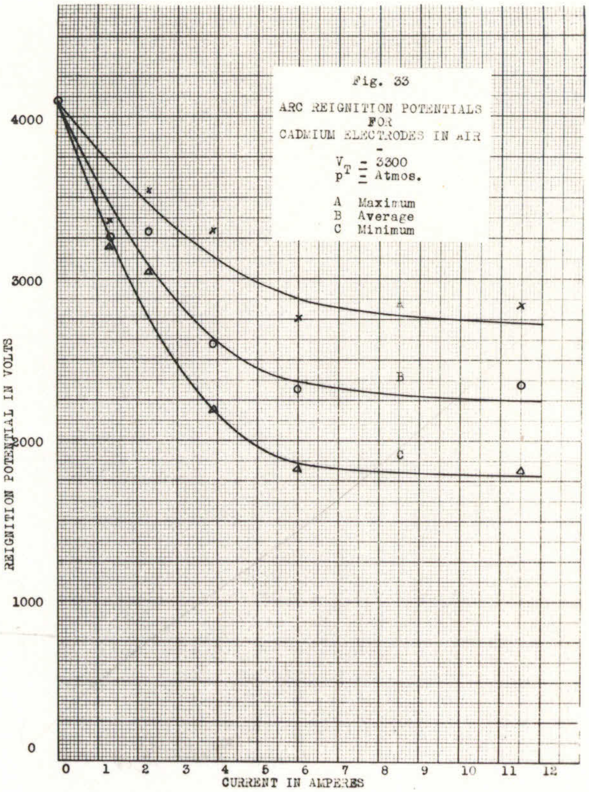


Fig. 33

ARC REIGNITION POTENTIALS
FOR
CADMIUM ELECTRODES IN AIR

$V_T = 3300$
p = Atmos.

A Maximum
B Average
C Minimum

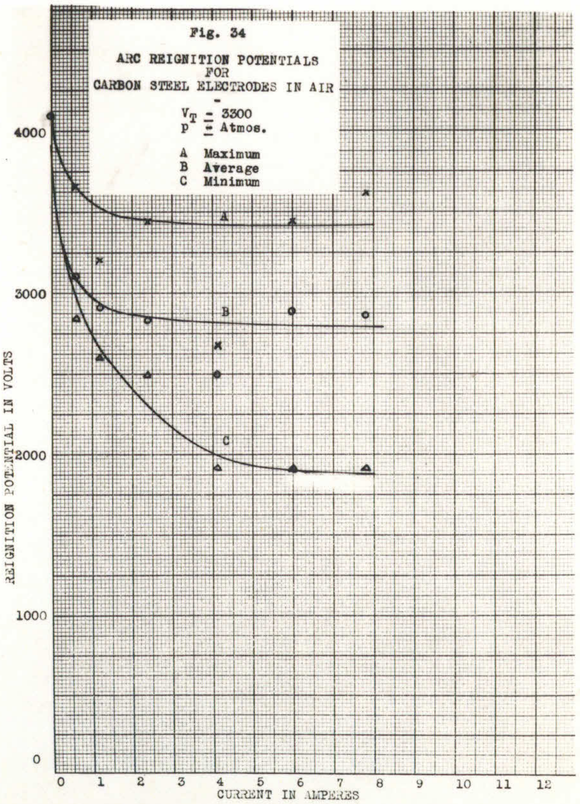


Fig. 34

ARC REIGNITION POTENTIALS
FOR
CARBON STEEL ELECTRODES IN AIR

$V_T = 3300$
p = Atmos.

A Maximum
B Average
C Minimum

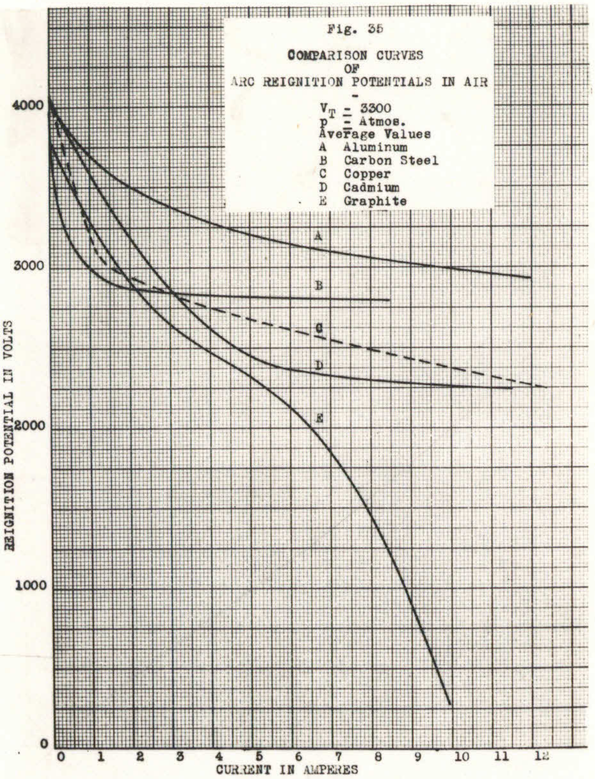


Fig. 35

COMPARISON CURVES
OF
ARC REIGNITION POTENTIALS IN AIR

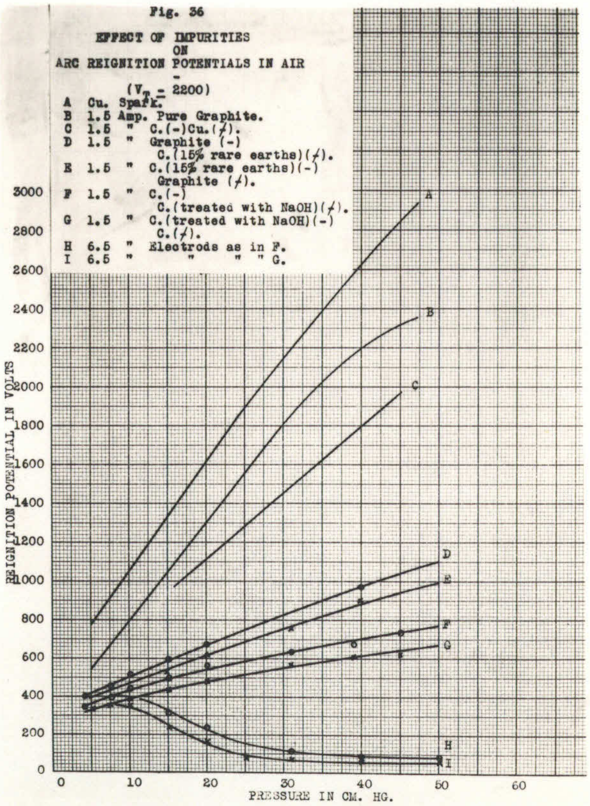


Fig. 36

EFFECT OF IMPURITIES
ON
ARC REIGNITION POTENTIALS IN AIR

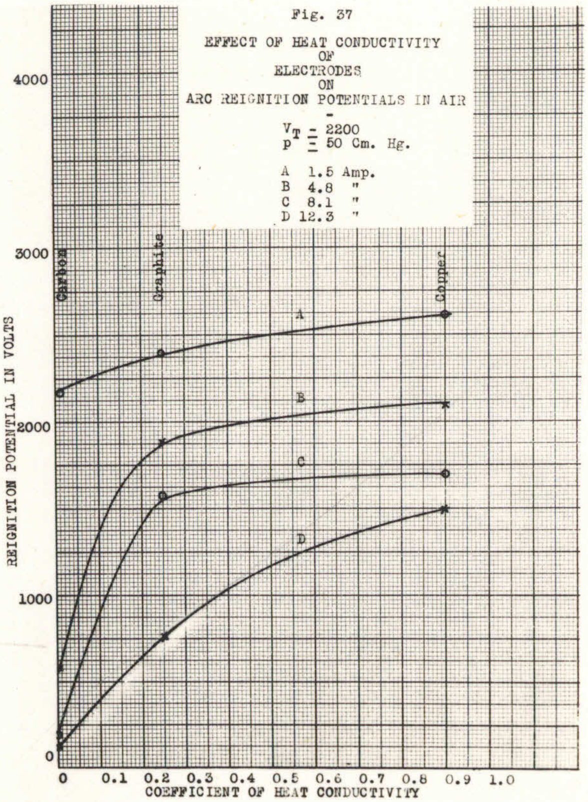


Fig. 37

EFFECT OF HEAT CONDUCTIVITY
OF
ELECTRODES
ON
ARC REIGNITION POTENTIALS IN AIR
-
$V_T = 2200$
$p = 50$ Cm. Hg.

A 1.5 Amp.
B 4.8 "
C 8.1 "
D 12.3 "

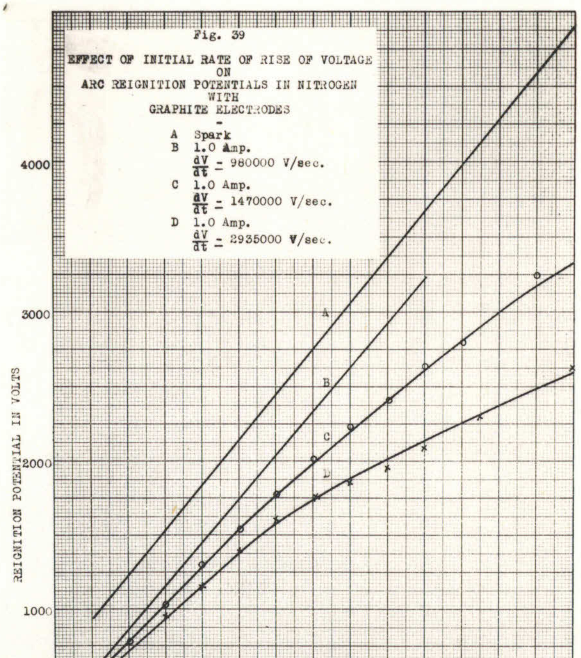


Fig. 39

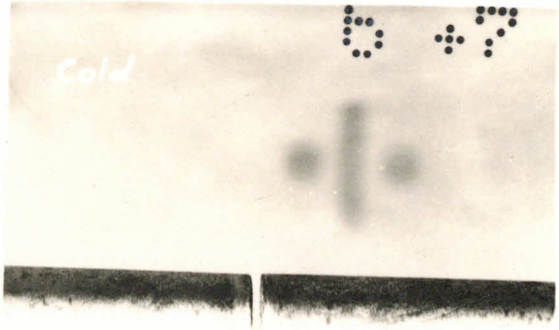
EFFECT OF INITIAL RATE OF RISE OF VOLTAGE
ON
ARC REIGNITION POTENTIALS IN NITROGEN
WITH
GRAPHITE ELECTRODES
-
A Spark
B 1.0 Amp.
$\frac{dV}{dt} = 980000$ V/sec.
C 1.0 Amp.
$\frac{dV}{dt} = 1470000$ V/sec.
D 1.0 Amp.
$\frac{dV}{dt} = 2935000$ V/sec.

Fig. 38

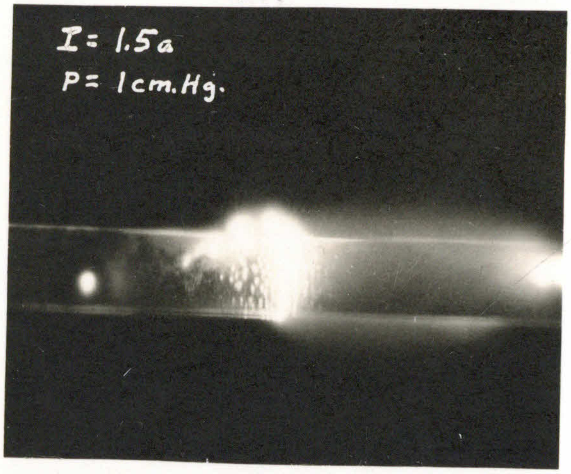
EFFECT OF PRESSURE AND CURRENT ON THE APPEARANCE OF THE ARC

Pure Graphite Electrodes

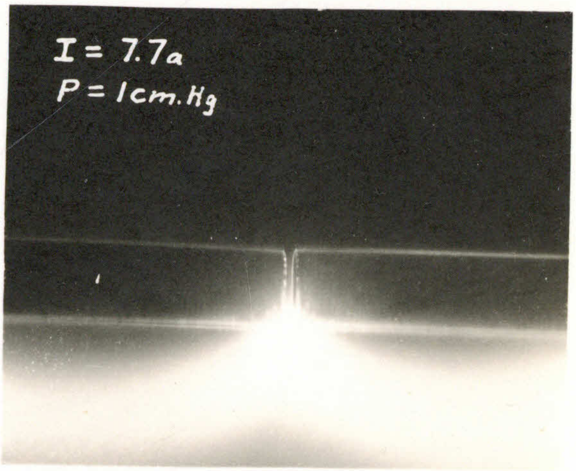
Exposure - 1/50 sec.



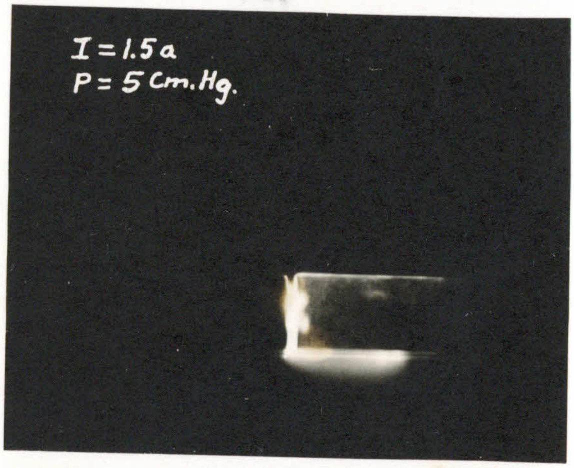
(a)



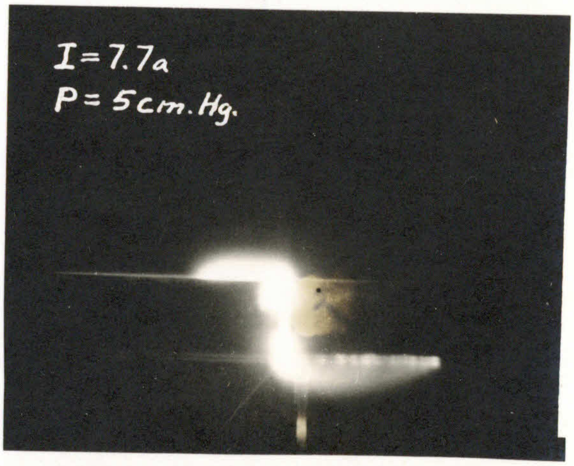
(b)



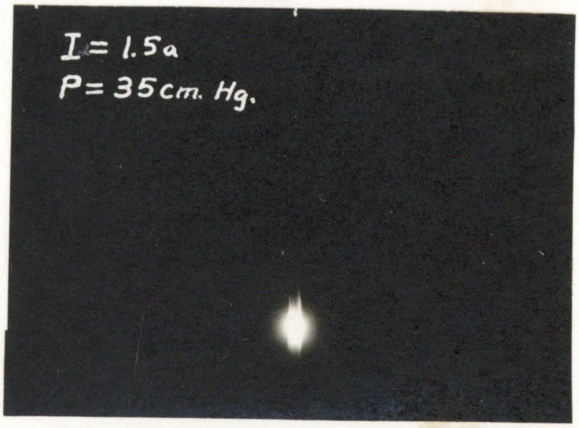
(c)



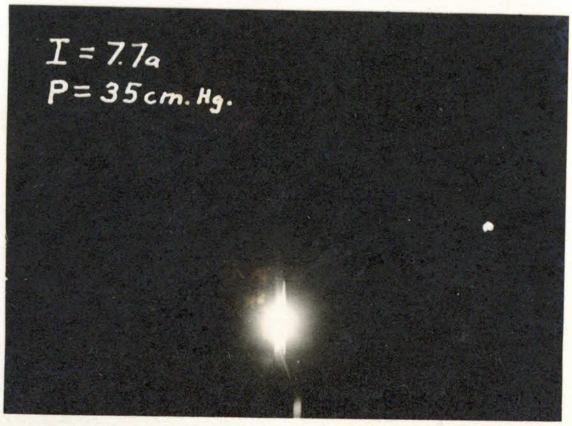
(d)



(e)



(f)



(g)

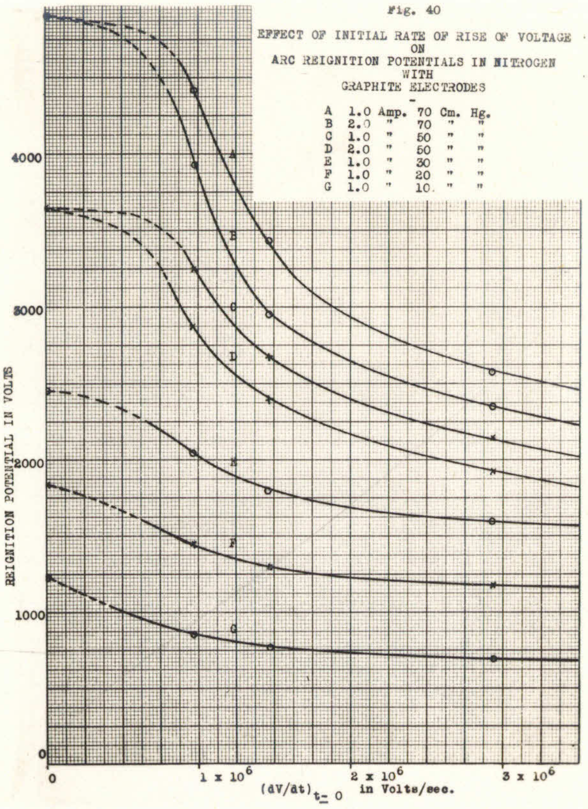


Fig. 40

EFFECT OF INITIAL RATE OF RISE OF VOLTAGE
ON
ARC REIGNITION POTENTIALS IN NITROGEN
WITH
GRAPHITE ELECTRODES

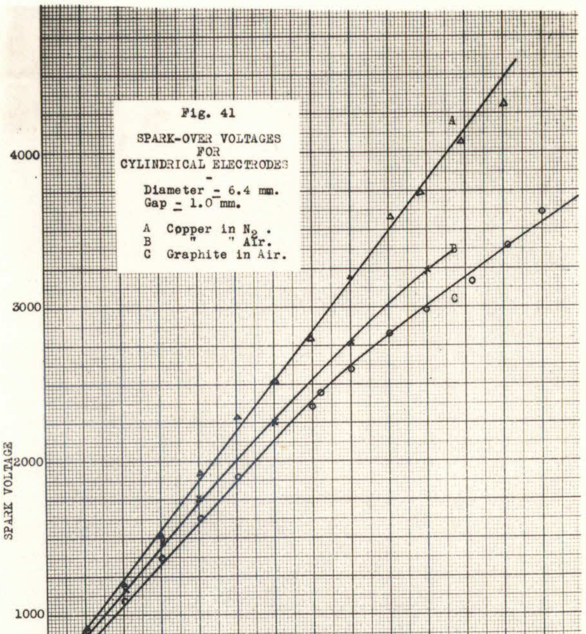


Fig. 41

SPARK-OVER VOLTAGES
FOR
CYLINDRICAL ELECTRODES

TABLES

TABLE 1

Summary of electrode materials listed in the order of decreasing reignition potential (left to right) for 70 cm. of Hg. and currents greater than 4 amperes, Fig. 35, with certain physical properties.

PROPERTY*	MATERIAL				
	Al. (Al_2O_3)	Steel (Fe_2O_3)	Cu. (CuO)	Cd. (CdO)	Graphite
Specific Heat	0.274	0.23	0.126	0.062	0.445
Coefficient of Heat Conductivity	1.01	0.107	0.9	0.216	0.24
Melting Point °C	659 (2050)	1530 (1541)	1080 (1064)	321	3600
Boiling Point °C	1800	2450	2310	778 (1000)	3600
a**	(3.3×10^{5})	(3.57×10^{3})	9×10^{5} (3.5×10^{-8})	(3.7×10^{-1})	7.45×10^{6}
$b^{**} \times 10^{4}$	(3.73)	(4.69)	5.02 (2.25)	(3.02)	5.49
ϕ***	3.57 (3.90)	4.72 (3.82)	3.71 (1.76)	(2.43)	3.93

* Oxide properties in parentheses.

** Thermionic constant for $I = a T^{\frac{1}{2}} \exp(-b/T)$.

*** Work function.

TABLE II

Summary of gases used with pure graphite together with their physical constants. Listed in the order of decreasing reignition potential (left to right), see Fig. 24.

	Gas			
1 amp. order	CO_2	O_2	Air	-
8 " "	CO_2	O_2	-	N_2
Molecular Weight	44	32		28
Ionizing Potential (volts)	14.3 (18,17,29)	13.5 (20)		16.5 (24)
Specific Heat	0.2169	0.2175	0.243	0.2497
Recombination Coefficient ($x\ 10^{-6}$)	1.657	1.612	1.603	
Mobility + ions - "	 0.76 0.81	 1.29 1.79	 1.37 1.80	 1.27 1.84
Attachment Coefficient*	$2.1x10^5$	$6.7x10^3$	$4.3x10^4$	
Critical Potential	(CO 5.97)	6.1		8.52
A**	20.0		14.6	12.4
B/A**	23.3		25	27
Cathode Drop Fe Cath.		350	269	215
Cu "			252	208
Al "		310	229	179

* Electron impacts to produce a negative ion.

** Constants for $b = A\ p\ \exp(-Bp/F)$ = number of iron pairs produced by a negative ion in 1 cm. drift. p = pressure F = electrostatic field. See reference 23 p.277.

APPENDIX

RESEARCH SUGGESTIONS

During the course of this research it has become apparent that certain questions regarding the factors affecting arc reignition and related phenomena should be answered if a more thorough knowledge of the arc was to be reached. However, these questions involved research projects beyond the scope of the present investigation and are therefore presented here as suggestions for further research in this field.

(a) The extension of the present investigation to pressures above atmospheric would prove interesting and valuable, and might uncover valuable properties of certain materials which would be useful in switching.

(b) The work covered in the present research was all for a circuit of very small reactance. The effect of lower power factors on the reignition and extinguishing potentials at various pressures and currents should be determined since most practical arc circuits are not of 100% power factor.

(c) It is suggested that a study be made of a considerable number of metals; determining the effect of impurities of any kind that might be present and also the effect of gases.

(d) It would be interesting and instructive to determine the critical dV/dt for arc extinction in an inductive circuit by the method used by Mr. T.E. Browne, Jr. in his studies of arcs in turbulent gases, for various gases at low pressures and also the effect of current upon this factor.

(e) By means of a full wave rectifier of thyratrons it would be possible to determine the effect of having each electrode always of the same polarity, instead of alternating as in the present work. Also by properly biasing the grids a study could be made of the effect of various durations of zero current upon the arc characteristics.

(f) The effect of frequency and initial dV/dt upon the reignition and extinguishing potentials should be determined for a greater range than was possible at this time.

(g) The influence of the various factors studied in this paper upon the extinguishing potential should be determined.

The above suggestions could be carried out with the present experimental set-up with a minimum of changes and additions.